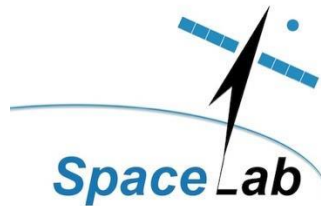




LOW COST AND PORTABLE SOFTWARE DEFINED RADIO GROUND STATION

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This dissertation is submitted in partial fulfilment of the requirements for
the degree of Master of Philosophy in Space Studies

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ABSTRACT

Small satellites are being launched by a multitude of private and public organizations around the world. They are innately cheaper than their large counterparts. This attribute, and additional ones, such as their easy-to-assemble nature and the convenience of using commercially available off-the-shelf parts to build them has enhanced their popularity. Now that getting into space has become more accessible there is an influx of information available from small satellites, however the information is not being utilized too efficiently on Earth. One reason as to why this is evident is because traditional ground stations, which are largely hardware dependent, are expensive to develop. However, with the introduction of Software Defined Radios (SDRs) many of the operations formerly done using hardware can now be implemented in software. Using a SDR can substantially reduce the cost of a traditionally hardware-based ground station. A number of universities and other organizations have or are developing SDR ground stations to communicate with satellites in different orbits. The ability to receive or transmit signals is important because it displays the capability to develop and operate satellites to various stakeholders.

This dissertation attempted to enhance the movement towards satellite communication using SDR technology by developing a low cost, portable, easy to assemble and extendable ground station at the University of Cape Town in order to make contact with one or more small satellites in Low Earth Orbit (LEO), to encourage data usage, national and international collaboration and education.

The ground station was constructed and tested based on its objectives, requirements and constraints. The commissioning tests were conducted in the SpaceLab at the University of Cape Town. The ground station was able to make contact with two small satellites in LEO successfully. Packets were received from two satellites that clearly stated who they were. The information contained in the packets was decoded into ASCII text and Hex code. They were compared with other successful amateur ground station results from all over the world to verify their authenticity. The main conclusion was that the SDR ground station was able to make contact with small satellites in LEO operating in the 70-cm band.

ACKNOWLEDGEMENTS

Dedicated to God and my family.

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1 INTRODUCTION

We begin by introducing this dissertation's mission statement to outline what it entails before successive topics are addressed. The remainder of the chapter then goes on to examine topics related to the mission statement in order to provide insight and background into mission statement.

1.1 Mission Statement

The mission statement provides insight into why this project was conducted. It was an elementary building block used to compile this dissertation and it is therefore continually referred back to throughout this dissertation. The mission statement is provided below.

Mission Statement

Small satellites are being launched by a multitude of private and public organizations around the world. They are innately cheaper than their large counter parts. This attribute, and additional ones, such as their easy to assemble nature and the convenience of using commercial off-the-shelf parts to build them has enhanced their popularity. Now that getting into space has become more accessible there is an influx of information available from small satellites, however the information is not being utilized to efficiently on Earth. One reason as to why this is evident is because traditional ground stations, which are largely hardware dependent, are expensive to develop. However, with the introduction of Software Defined Radios (SDRs) many of the operations formerly done using hardware can now be implemented in software. Using a SDR can substantially reduce the cost of a traditionally hardware-based ground station. A number of universities and other organizations have or are developing SDR ground stations to communicate with satellites in different orbits. The ability to receive or transmit signals is important because it displays the need to develop and operate satellites to various stakeholders.

This dissertation forms part of the movement towards satellite communication using SDR technology by developing a low cost, portable, easy to assemble and extendable ground station at the University of Cape Town in order to make contact with one or more small satellites in Low Earth Orbit (LEO), to encourage data usage, national and international collaboration and education.

Relevant topics pertaining to the above mission statement are discussed in the remainder of this chapter.

1.2 Satellites and Ground Stations

This section introduces characteristics associated with space orbits to provide information about the environment in which small satellites operate. It then defines and addresses small satellites in order to distinctly show which satellites belong to this particular group. The next section deals with radio communication to demonstrate how small satellite signals propagate through space and it also describes what devices are suited to receiving those signals. The last section defines the structure of a typical small satellite ground station to identify the general components utilized in satellite telemetry reception on Earth.

1.2.1 Satellite Orbits

An orbit, in terms of a satellite in outer space, is an elliptically closed path that a manmade or natural satellite takes around another object in space.[1] This dissertation focuses on manmade satellites more specifically, small satellites orbiting around Earth.

A satellite is able to stay in an orbit if it has enough speed to retrace its elliptical path around the body it is orbiting, according to Kepler. Objects on the surface of the Earth experience a gravitational pull of $9.8m \cdot s^{-2}$. Objects orbiting Earth also experience Earth's gravitational pull but in varying degrees. The closer an object is to the Earth, the higher the velocity it needs to maintain its orbit. This is because the object will experience a higher force of attraction closer to the Earth as opposed to far away from it. [2], [3] An equation used to calculate the velocity an object requires to maintain its orbit around the Earth is given by:

$$v^2 = \frac{GM}{r} \quad \text{Equation 1.1}$$

where,

v = velocity of the object orbiting a body ($m \cdot s^{-1}$)

G = gravitational constant ($N \cdot \frac{m^2}{kg^2}$)

M = mass of the body (kg)

r = distance from the body's centre to the object (m)

Solving for v in Equation 1.1 it is evident that the velocity an object requires to stay in orbit around Earth is dependent on its distance from the centre of the Earth. The higher the value of r , the lower the velocity and the lower the value of r , the higher the velocity it requires according to Equation 1.1. For example, an object located 500km above the Earth's surface, in an area called LEO, would have to have a velocity of $7615m \cdot s^{-1}$ to remain in orbit, where

$$G = 6.67 \times 10^{-11} \text{ N} \cdot \frac{\text{m}^2}{\text{kg}^2}$$

$$M = 6.0 \times 10^{24} \text{ kg}$$

$$r = 6900000 \text{ m}$$

As mentioned, before, an orbit takes on an elliptical shape, however this is not the only way to distinguish or describe an orbit. Table 1.1 shows some important terms used to describe an orbit and their definitions. These definitions are described in terms of an object orbiting Earth, but they apply to any gravitationally bound object. [2], [3]

Table 1. 1 Orbit features and their definitions. [3]–[5]

Feature	Definition
Period	Time it takes a satellite (manmade/ natural) to complete one orbit around Earth.
Apogee	The farthest point that a satellite is from Earth.
Perigee	The closest point that a satellite is from Earth.
Inclination	The angle that the orbital plane makes in relation to the Earth's equator.
Orbital Velocity	The speed a satellite needs to maintain to stay in its desired orbit around Earth.
Eccentricity	The shape of the orbit around Earth.
Attitude	The distance between a satellite and the Earth's surface.

Orbits are widely described by their altitude above the Earth and their periods. The closest orbits to Earth are called Lower Earth Orbit (LEO), the orbit that this dissertation primarily focuses on. Medium Earth Orbit (MEO) are a bit further out (2000km -35780km) followed by High Earth Orbit (HEO) which are higher than 35780km. Figure 1.1 shows LEO, MEO and HEO orbital regions in relation to the Earth.

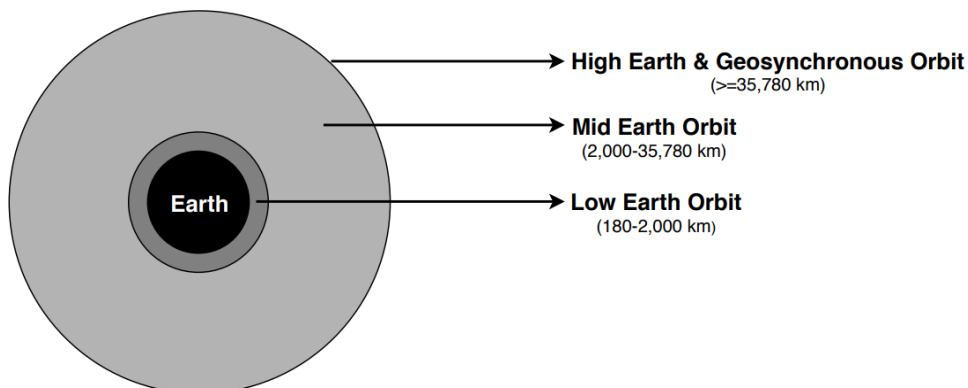


Figure 1. 1 LEO, MEO and HEO in relation to Earth. [6]

LEO

LEO is approximately 180-2000 km above the surface of the Earth, with a corresponding orbital period ranging from 90- 128 minutes. [6], [7] Financially and technically LEO is less demanding to get to as compared to MEO and HEO. In view of

this small satellites are predominantly found in this orbit. [1] LEO satellites are predominantly used for scientific research, communication and imaging because of its advantageous low altitude. Hobbyists, universities and start-ups are attracted to this orbit due to its favourable conditions which they can exploit. On the other hand, such a huge attraction to this orbital region has led to major space debris problems which pose a risk for future manned and unmanned space missions. [8],[9]

Sun-Synchronous Orbit (SSO), located within LEO, exhibits an interesting characteristic that allows a satellite to cross over the Earth's equator at an instant when the local solar and ground time are equal. Figure 1.2 depicts the trace a satellite would make each time it crosses the equator at the same time. Even though keeping a satellite in this orbit requires regular adjustments to overcome atmospheric drag and the tug of the Sun and Moon's gravity, satellites launched into this orbit are privy to an appealing feature. Launching an imaging satellite into a SSO is of particular interest to scientists who want to build up a comparative catalogue of images, taken under similar lighting conditions over years, without major distorting effects caused by changes in shadows and lighting. This is possible because SSO maintains the angle of sunlight on the surface of the Earth in a season. Climate change is also an area that has benefited positively from this orbit because scientists were and are still able to visualise changes in a location under similar sunlight constraints. [6]

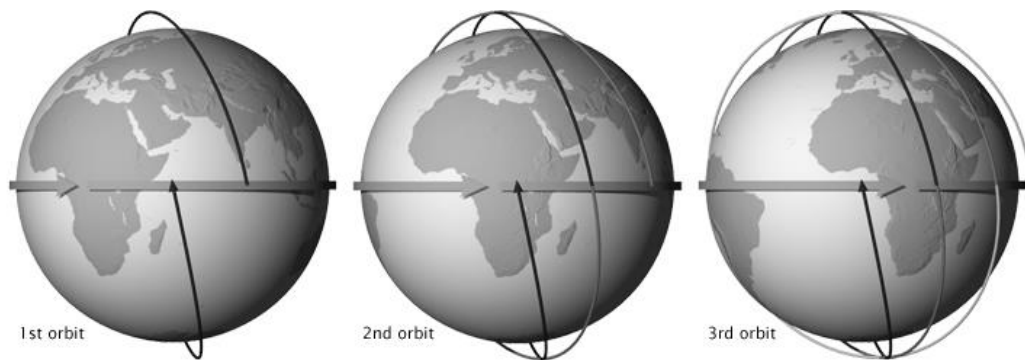


Figure 1. 2 The trace of a satellite orbiting in SSO. [6]

A polar orbit or a near polar orbit, shown in Figure 1.3, is another special type of orbit in LEO. A polar orbit has an inclination of approximately 90° to the equator so satellites within it, orbit from pole to pole. Satellite missions aimed to monitor crops, forests and global security are ideally suited to polar orbit. [10] Polar orbits however are disadvantageous because they inhibit a satellite from continuously viewing a single location on the Earth like SSO. [11]

Near Polar Orbits

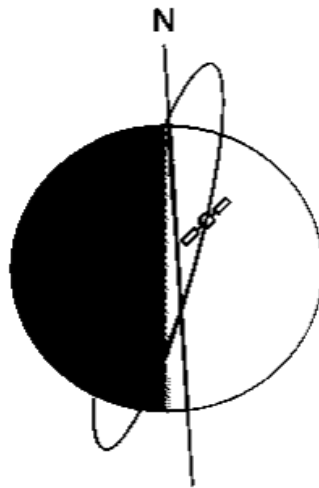


Figure 1. 3 A depiction of a near polar orbit. [12]

MEO

MEO, as shown in Figure 1.1, is approximately 2000-35780 km above the surface of the Earth with an orbital period between 2-12 hours.[13] Semi-Synchronous Orbits and Molniya orbits are two prominent types of MEO orbits. Semi-Synchronous Orbit is about 20200 km above the Earth's surface with an orbital period of 12 hours. A satellite in this orbit is able to visit the same two areas located over the equator in a 24 hours. Navigation satellites such as the Global Positioning System (GPS) make use of this orbit. The second orbit, Molniya, is good for satellites that are designed to observe high latitudes because it has a high inclination value of 63.4° and a high eccentricity value of 0.722. This allows areas located at high latitudes on Earth and closer to the orbit's apogee to be seen for a greater time, roughly (8 hours) than areas found at low latitudes located around the orbit's perigee within its 12 hour orbital period. [6]

HEO

HEO, as shown in Figure 1.1, is located above 35780 km, with an orbital period around 24 hours. At 42,164 km an orbit known as Geosynchronous Earth Orbit (GEO) is located within HEO. At this altitude the satellite takes exactly as long to complete an orbit as the Earth takes to spin once around its axis, 24 hours. If a satellite is placed in circular GEO, over the equator, the satellite is said to be in Geostationary Orbit (GSO). A satellite in GSO will have a footprint directly over the same place on Earth as well so GSO is an ideal location for weather satellites. When they are placed in this orbital region they can monitor weather and solar activity in an area constantly. GSO is also good for communication satellites that provide television, telephonic and radio services to Earth. [6] GEO and GSO are shown in Figure 1.4 in relation to each other.

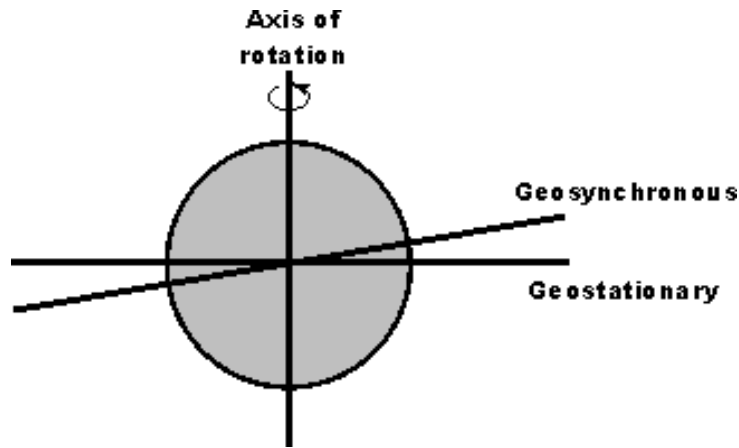


Figure 1. 4 GEO and GSO in relation to each other.[14]

1.2.2 Radio Communications with Satellites

Communication with satellites is possible through electromagnetic waves, in the range of 0.003 – 300000 MHz. [15] This dissertation focuses on radio communication between small satellites in LEO and ground stations located on Earth. Figure 1.5 depicts the commonly used radio bands.

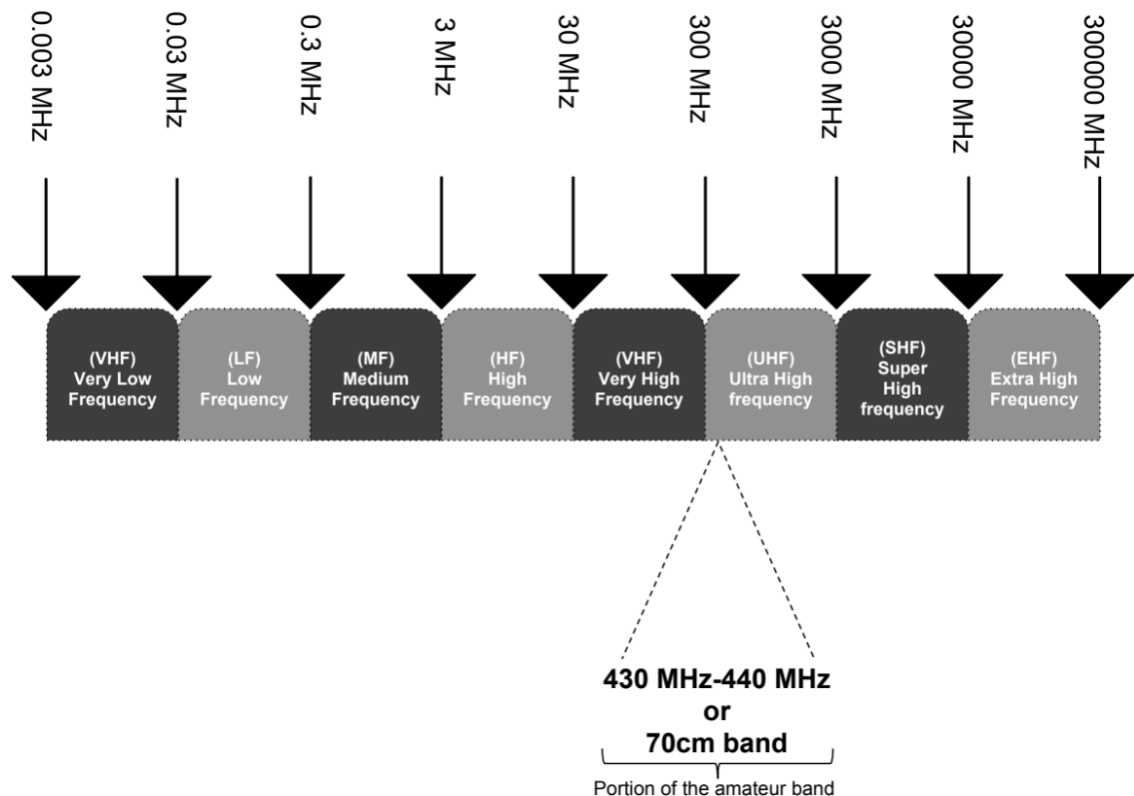


Figure 1. 5 The location of the 70-cm band in the Radio portion of the electromagnetic spectrum.

Figure 1.5 highlights the 70-cm band (430 MHz – 440 MHz) located in the Ultra High Frequency (UHF) band, the band of interest in this dissertation because a number of

small satellite missions' downlink within this band. The 70-cm band is part of a larger group of radio frequencies allocated to amateur radio. Amateur radio frequencies and all other radio frequencies are allocated to different sectors by the International Telecommunications Union (ITU), a specialised agency of the United Nations (UN). [16] At a national level specifications and technical regulations are controlled by local government and all radio activity must adhere to the rules set out by local government. Amateur radio specifically defines a section of the radio frequency spectrum used for non-commercial objectives such as communicating with other amateur radio enthusiasts or communicating with satellites in outer space. [17] In South Africa, one has to possess an amateur radio license in order to transmit radio frequencies. Appendix A summarises information needed to obtain an amateur radio license in order to transmit within the amateur radio band. Aspects such as the cost, examination dates and types of licenses are presented in Appendix A.

In order to transmit to or receive data from a small satellite in LEO, operating within the amateur band, an antenna with specific characteristics must be used. The definition of an antenna and its characteristics is discussed below.

Antenna

An antenna is an instrument that acts as an interface between a directed wave and a radiated wave, or the reverse. [18]

Antenna Radiation Pattern

An antenna radiation pattern is a mathematical function or a graphical depiction that represents radiation properties presented by an antenna as a function of space coordinates. [19] It essentially describes how energy is radiated to and away from an antenna. An antenna pattern is three dimensional, however it is quite frequently represented in two dimensions, commonly referred to as principal plane patterns, as shown in Figure 1.6 When representing antenna patterns in this form some information can be lost so it is recommended to only represent patterns that won't lose important amounts of information in a two-dimensional format. Principle plane patterns are formulated by cutting the three- dimensional pattern through its maximum value or by direct measurement. Two common terms commonly associated with the principle plane patterns are the terms azimuth and elevation. Azimuth refers to the horizontal plane represented by the x-y plane in Figure 1.6. The elevation plane refers to the vertical plane represented by the y-z plane in Figure 1.6. [18]

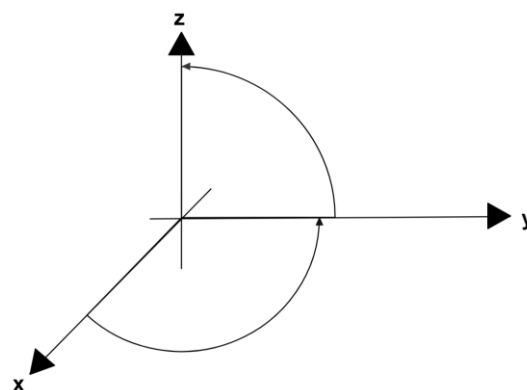


Figure 1. 6 Principal plane patterns.[18]

Radiation patterns are sometimes represented in polar co-ordinates since it is easier to visualise how the antenna radiates in multiple directions. Another way to represent a radiation pattern is by using a Cartesian plane, however this way is only useful if the levels of the lobes in the radiation pattern are not of importance. [18] An example of a radiation pattern in polar co-ordinates and in a Cartesian plane is shown in Figure 1.7 below.

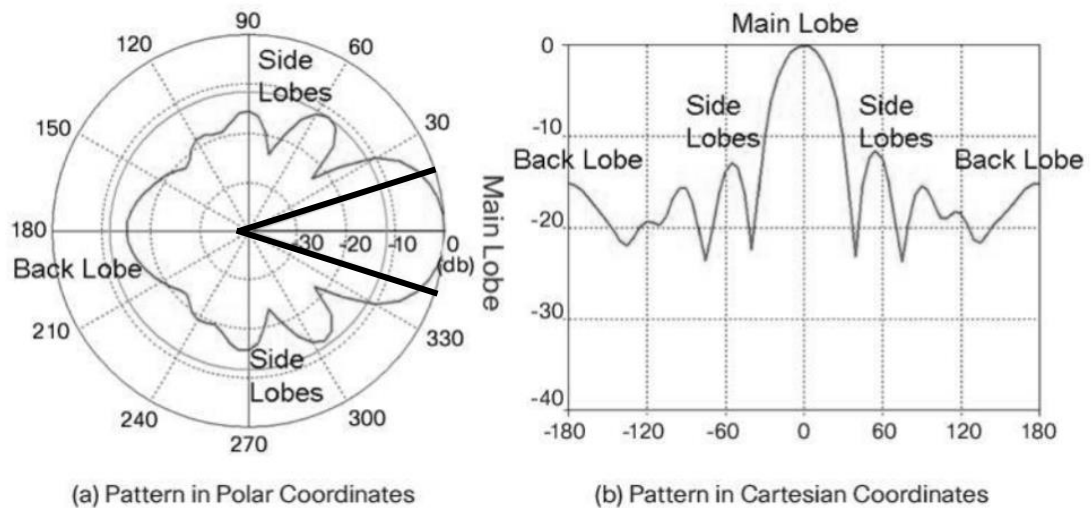


Figure 1. 7 A radiation pattern represented in polar and Cartesian co-ordinates. [18]

The four common types of radiation patterns are omnidirectional patterns, pencil-beam patterns, fan-beam patterns and shaped beam patterns. Omnidirectional patterns are typically shaped as a doughnut in a three-dimensional view, as shown in Figure 1.8, and a figure-eight pattern in two dimensions, as shown in Figure 1.9.

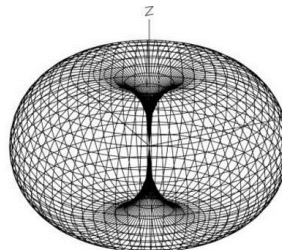


Figure 1. 8 Omnidirectional half-wave dipole antenna's radiation pattern in 3-D. [20]

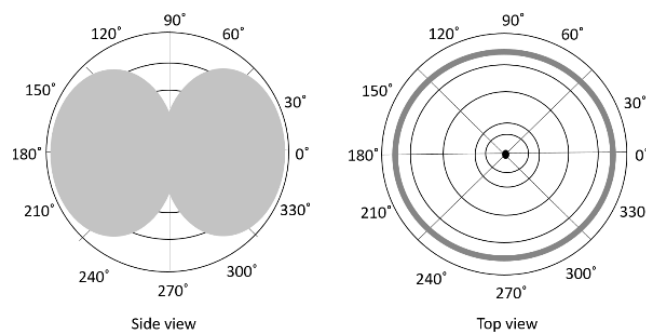


Figure 1. 9 Omnidirectional half-wave dipole antenna's radiation pattern in 2-D. [20]

Pencil-beam patterns, directional patterns, have sharp directional pencil shaped patterns as shown in Figure 1.10.

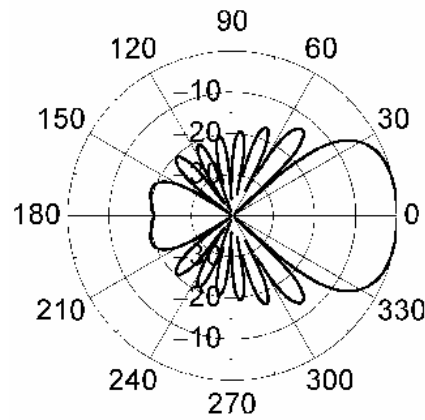


Figure 1. 10 A pencil-beam radiation pattern of an end-fire array. [21]

Fan-beam patterns are, like their name suggests, shaped in a fan pattern as shown in Figure 1.11.

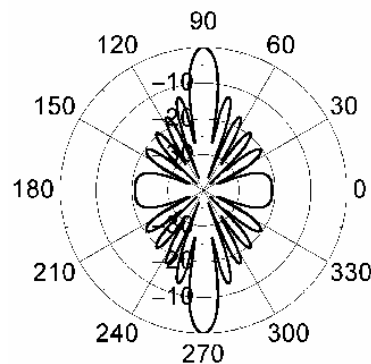


Figure 1. 11 A fan beam radiation pattern of a broadside array. [21]

Lastly, shaped beam patterns encapsulate radiation patterns that are non-uniform and pattern-less as shown in Figure 1.12.

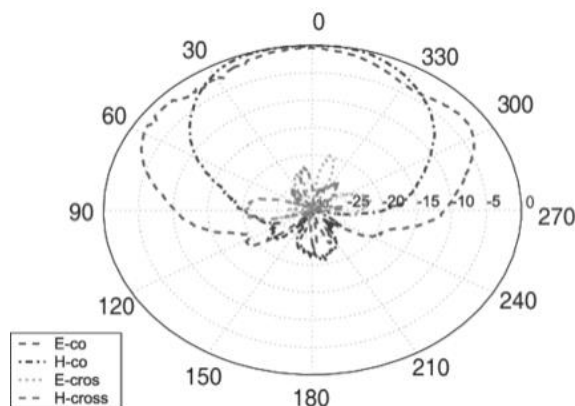


Figure 1. 12 An example of a non-uniform radiation pattern. [22]

Isotropic radiation is the referential point for all these types of radiation described and shown above. It is considered and discussed below.

Isotropic Radiator

An isotropic radiator is a theoretical lossless antenna that radiates energy uniformly in all directions and consequently has a unity gain in all directions. Antennas are assessed with respect to this radiator thereby making it their reference point. Such an antenna or radiator would have a spherical radiation pattern, as shown in Figure 1.13, and it would have circular principal plane patterns. [12]

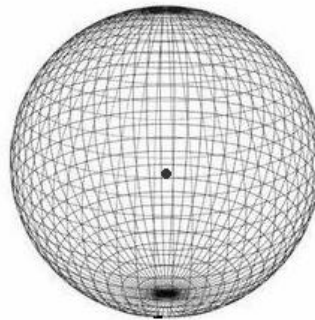


Figure 1. 13 A spherical radiation pattern of an isotropic radiator. [23]

Equivalent Isotropic Radiated Power (EIRP) is defined as, “The amount of power that an isotropic antenna radiates to produce the peak power density observed in the direction of maximum antenna gain”, according to its standard definition. EIRP with respect to an antenna describes an antenna’s radiation focussed in a certain direction where its radiation is equivalent to that particular antenna’s isotropic radiated power. [20]

Lobes

Lobes are areas found in antenna radiation patterns. They describe the amount and direction of radiation associated with the antenna. Lobes are generally located between areas of low radiation. Figure 1.7 displays the main, side and back lobes in a radiation pattern.

The main lobe or major lobe, within a radiation pattern, covers the greatest area. The maximum amount of radiation is found and directed in this lobe. [20]

Side lobes also known as minor lobes are spread laterally within a radiation pattern. Power is squandered in these lobes. [20]

The back lobe is located directly behind the main lobe. It also falls under the definition of a minor lobe since energy is wasted in this area as well. [20]

Gain

Gain is the ratio of power gain of an antenna in a particular direction with the power gain of a theoretical antenna in the identical direction. An isotropic radiator and a

dipole theoretical antenna are commonly used as theoretical antennas. When using an isotropic radiator, the gain is measured in dBi, otherwise known as decibels relative to an isotropic radiator or isotropic norm. On the other hand, when using the theoretical dipole, the gain is measured in dBd known as decibels relative to a dipole. Equation 1.2 shows how gain is calculated with reference to the isotropic radiator. In order to convert from dBi to dBd Equation 1.3 can be used. [12] It is common to represent gain relative to an isotropic radiator or theoretical dipole, but it is important to note that there are other ways to represent gain.

$$G = 10 \log \frac{N}{I} = 10 \log N, \text{ since } I = 1 \quad \text{Equation 1.2}$$

where,

$G = \text{Gain}(dBi)$

$N = \text{Numeric Gain}(dBi)$

$I = \text{Isotropic Gain}(dBi)$

$$dBd = dBi + 2.2 \quad \text{Equation 1.3}$$

3-dB beamwidth/ Half power beamwidth

A 3-dB beamwidth can be found in each principal plane. It is defined as the angle between the half-radiated power of an antenna's main lobe pattern. The polar plane figure in Figure 1.7 depicts the 3-dB beamwidth angle in between the thick black lines moving out from the centre to the rightmost edge. As a rule of thumb, when an antenna has a wide beamwidth it will have a low gain and when it has a narrow beamwidth it will have a high gain. [12]

Front-to-back ratio

A measurement used to describe the amount of power 180 degrees away from the peak radiated power in a directional antenna. [12]

Polarization

When an antenna radiates an electromagnetic wave, the wave fluctuates in time as it propagates through space. There are different types of polarization for instance, if an antenna's wave propagates outwards through space in an up and down motion (vertically) or in a left to right motion (horizontally) the antenna is said to be linearly polarized. If the antenna's wave spins out, the antenna is said to be elliptically

polarized. Lastly if an antenna's wave moves out in a circular manner then the antenna is said to be circularly polarized. [12]

Voltage Standing Wave Ratio (VSWR)

VSWR is the ratio of the maximum voltage of an antenna to its minimum voltage. It describes the amount of power that an antenna receives compared to the amount of power the antenna reflects. [12] VSWR also describes how well matched an antenna is to its feed line. A VSWR of 2 describes an appropriately matched antenna. If an antenna has a VSWR value that exceeds 2 then it is considered to be poorly matched antenna. [14]

Directional antenna

Directional antennas are designed to radiate power efficiently in a particular direction. Such antennas generally have one main lobe and multiple minor lobes. They are used to eliminate noise from surrounding objects when trying to communicate with a target in a specific direction. Examples of directional antennas include yagis, patches and dishes. [12]

Omnidirectional antenna

An omnidirectional antenna radiates a similar amount of power in all directions. [15] If horizontal coverage is needed in all directions from an antenna with multiple grades of vertical coverage, then an omnidirectional antenna is a good choice. [16] Dipoles and collinear antennas are examples of omnidirectional antennas.

1.2.3 Small Satellites

In terms of their mass small satellites are commonly described in two different ways. The two definitions are presented below.

- a) Small satellites sometimes referred to as, "miniature satellites", are artificial satellites with masses between 100-500kg including their fuel. [17]–[20]
- b) Small satellites are artificial satellites with masses 500kg or less including their fuel. [17]–[20]

Definition b) will be used in this dissertation because it encompasses a wider group of satellites. Table 1.2 displays characteristics associated with five major small satellite groups.

Table 1. 2 Small Satellite Classification. [24]–[34]

Type	Weight (kg)	Functions	Example
Mini	100-500	<ul style="list-style-type: none"> • Telecom constellation • Message data relay • Remote sensing • Systems receiving signals from ground or sea-based sensors • Meteorological • Scientific Experiments 	<ul style="list-style-type: none"> • French: PARA SOL • Chilean: Sistema Satelital para Observación de la Tierra (SSOT) • ESA: Smart-1
Micro	10-100	<ul style="list-style-type: none"> • Message data relay • Systems receiving signals from ground or sea-based sensors • Meteorological • Scientific Experiments • Student and University Experiments 	<ul style="list-style-type: none"> • Swedish: Astrid-1 • Swedish: Astrid -2
Nano	1-10	<ul style="list-style-type: none"> • Student and university experiments 	<ul style="list-style-type: none"> • Indian: Indian National Satellite System -3A (INSAT 3A) • American: PhoneSat • Austrian: Pegasus
Pico	0.1-1	<ul style="list-style-type: none"> • Student and university experiments 	
Femto	<0.1	<ul style="list-style-type: none"> • Student and university experiments 	<ul style="list-style-type: none"> • Indian- KalamSAT • American - Pico-Satellite Solar Cell (PSSC)

1.2.4 Small Satellite Ground Stations

Every ground station that is built is designed to carry out a particular service or services. Article 1, Section III (1.19) in the 2016 ITU Radio Regulations Articles document defines a radio service to be a:

“transmission, emission and/or reception of radio waves for specific telecommunication purposes.” [35]

Article 1, Section IV (1.6) in the 2016 ITU Radio Regulations Articles document defines a station to be:

“One or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary at one location for carrying on a radiocommunication service, or the radio astronomy service.” [35]

The ITU lists and describes 41 types of services and 53 types of stations. [36] Article 1, Section III (1.57) titled “amateur-satellite service”, describes the type of service the ground station this dissertation aims to provide. It states that an amateur-satellite service is:

“A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service.” [35]

Article 1, Section III (1.96) titled “amateur station”, describes the ground station this dissertation aims to develop. An amateur station is described as:

“A station in the amateur service.” [35]

Radio ground stations may have different arrangements and can be mainly based in software, hardware or in a combination of the two. Figure 1.14 displays traditional elements that make up an amateur radio ground station and Figure 1.15 shows some accessories that can be used to enhance the basic set up. Not all the elements shown in either diagram are essential for an amateur ground station to be functional. For instance, a microphone would not be needed if the amateur ground station is only meant to receive data and not send verbal data.

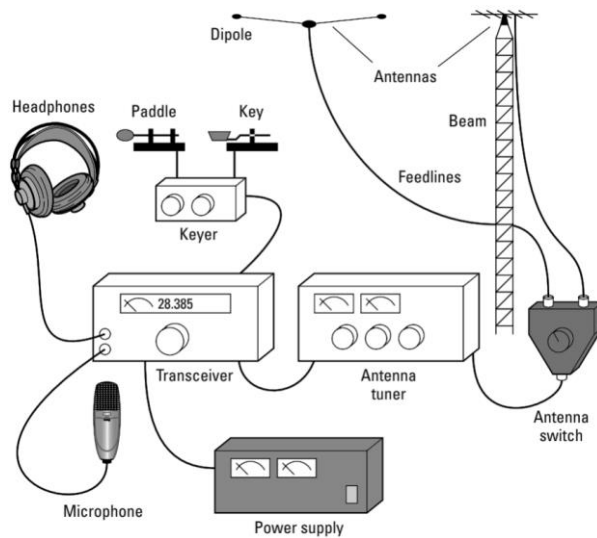


Figure 1. 14 The basic set up of an amateur satellite ground station.[37]

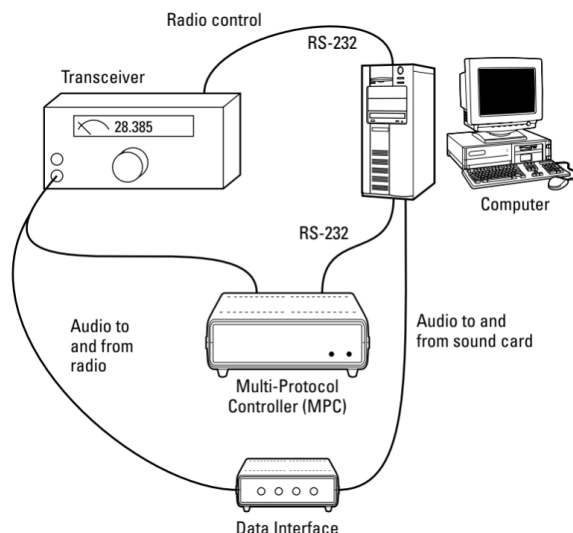


Figure 1. 15 Amateur ground station accessories. [37]

This dissertation aims to develop a software-defined radio amateur ground station that receives data from small satellites in LEO. The general layout for a receive-only software defined radio amateur station is shown in Figure 1.16. Chapter 2 will expand upon the different elements of this diagram. Figure 1.17 divides the six elements

shown in Figure 1.16 into three layers namely the, “Physical Layer”, “Physical and Software Layer” and the, “Software Layer”. Some elements are composed of both hardware and software hence they are placed under the, “Physical and Software Layer”. For the purpose of this dissertation the software defined radio amateur ground station will be referred to as the Software Defined Radio (SDR) ground station or ground station from now onwards.

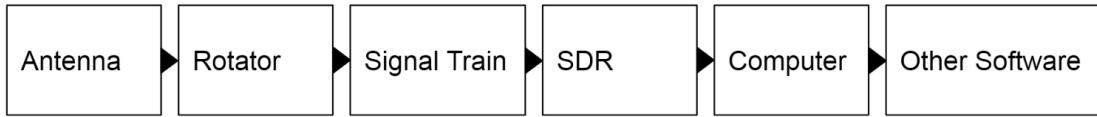


Figure 1. 16 The general layout and flow of a software defined ground station.

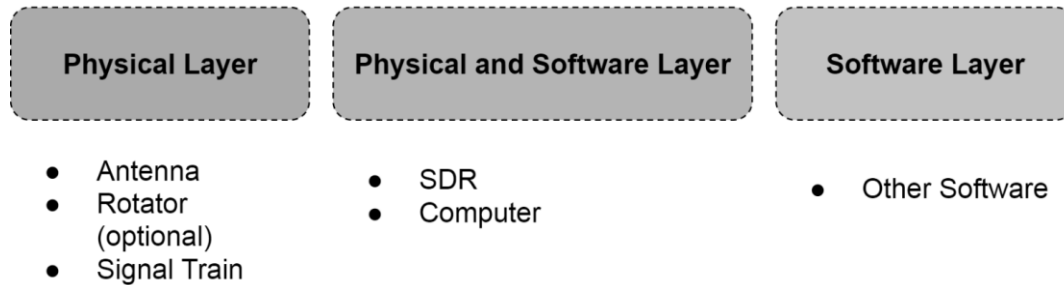


Figure 1. 17 Software defined radio ground station.

1.3 Small Satellite Missions

Ground stations are normally aligned with a space mission. The ground station developed in this dissertation aims to make contact with a number of small satellites to increase the possibility of information sharing. The First Kenya University Nano Satellite-Precursor Flight (1KUNS-PF) ground station team offered advice throughout various stages of this dissertation, so the 1KUNS-PF satellite mission is covered here for that reason. It also highlights a describes how a typical small satellite mission may come into fruition.

1.3.1 KiboCUBE Program

The United Nations Office for Outer Space Affairs (UNOOSA) through its, “United Nations Programme on Space Applications”, is geared towards facilitating and promoting successful international co-operation and capacity building in the space sector. In 2009, UNOOSA initiated the Basic Space Technology Initiative (BSTI), to improve access of developing countries to space technology and related expertise. [38]

The Japan Aerospace Exploration Agency (JAXA) is involved in areas such as manned space flight; satellites; launch systems and research. Through their continued efforts in

the space sector in 2008 they developed the Japanese Experiment Module (JEM) called, “Kibo”, located on the International Space Station (ISS).

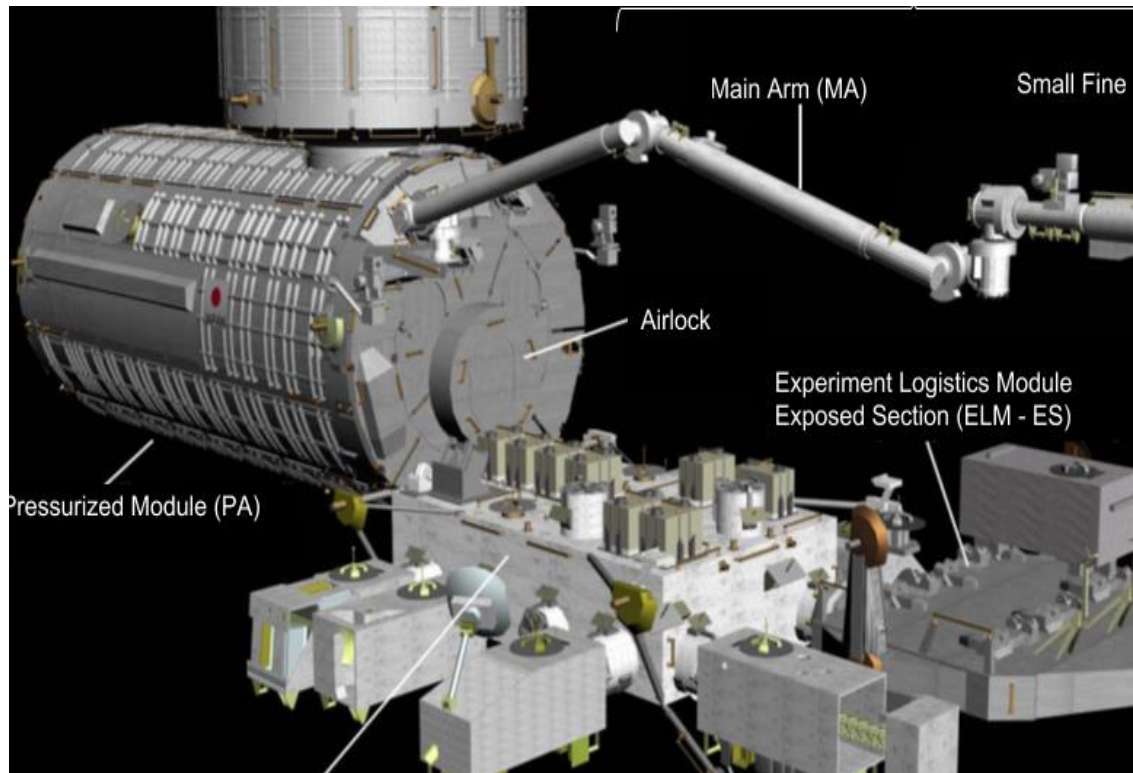


Figure 1. 18 A diagram of Kibo. Adapted from. [39]

Kibo, shown in Figure 1.18, is composed of multiple parts. However, its unique airlock system, a system that allows experiments to be transported into space, and its robotic arms, which among many tasks aid the exchange of experimental payloads, have distinguished Kibo to be the only way to deploy satellites from the ISS. Kibo deployed its first JAXA developed satellite in 2012. After a successful satellite deployment, a multitude of countries have made use of this unique facility. Through Kibo, JAXA has managed to positively aid technology development and capacity building in space engineering. [38], [40]

In 2016, the KiboCUBE program was developed through the collaboration of the United Nations Office for Outer Space Affairs (UNOOSA) and the Japan Aerospace Exploration Agency (JAXA). The program was designed to deploy CubeSats from developing countries affiliated to the United Nations (UN). The CubeSats that are chosen need to be manufactured from educational and research institutions and it is hoped that through this endeavour space science and technology are promoted for sustainable growth and enhanced through capacity building. [38] The union between JAXA and Kenya also supports some of the seventeen Sustainable Development Goals (SDGs) outlined in the UN's Agenda 2030. The KiboCUBE program is of importance because it deployed the First Kenya University Nano Satellite-Precursor Flight (1KUNS-PF) into space. 1KUNS-PF was chosen to be deployed from the ISS through the KiboCUBE program from a number of entrants in August 2016, shortly after the KiboCUBE program was established. 1KUNS-PF was handed over to JAXA on the 16th January 2018; launched to the ISS on the 2nd April 2018 and deployed from Kibo using its robotic arms on the 11th May 2018. [39]

1.3.2 First Kenya University Nano Satellite-Precursor Flight

First Kenya University Nano Satellite-Precursor Flight, built by the University of Nairobi in conjunction with ASI-Sapienza, is a precursor mission to the Italy-Kenya University Nano-Satellite (IKUNS) mission. Table 1.3 provides details about 1KUNS-PF.

Table 1. 3 1KUNS-PF attributes.[41]–[43]

Aspect	1KUNS-PF
Mission Type	Technology demonstration Earth observation
Operator	University of Nairobi and ASI-Sapienza
COSPAR ID	1998-067NQ
SATCAT no.	43467
Spacecraft Type	1U CubeSat
Launch Mass	1 kg
Dimensions	10cm cubed
Launch Date	2 April 2018 UTC
Launch Site	Kennedy LC-39A
Contractor	Falcon-9 v1.2 (SpaceX)
Entered Service	11 May 2018, 10:51 UTC
Reference System	Geocentric
Orbit	LEO
Semi-Major Axis	6778.8 km
Eccentricity	0.0004315
Inclination	51.64 °
Apogee	400 km
Perigee	397 km
Mean Motion	15.56272555 rev/ day
Downlink/ Uplink Frequency	437.3000 MHz @9600bps /1200bps
Antenna Polarization	Circular
Period	93 min

Both the 1KUNS-PF and IKUNS missions were established by the Italy-Kenya University Nano-Satellite program in 2015. Figure 1.19 shows the relationship between Italy and Kenya that allowed this program to be established.

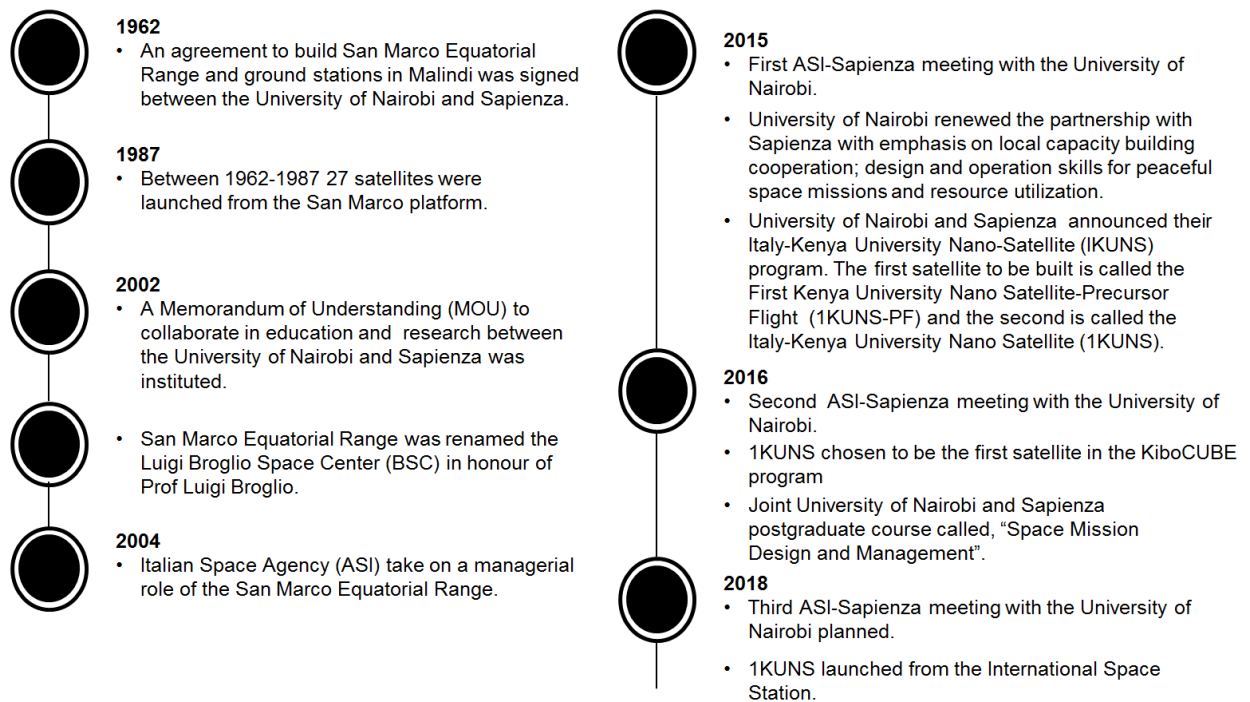


Figure 1. 19 A timeline showing the relationship between Italy and Kenya that led up to the creation of 1KUNS-PF. [44]–[46]

1KUNS-PF, a 1U CubeSat, consists of two identical ArduCam optical payloads that are positioned on opposite axes. [44] The ArduCam is the first Serial Peripheral Interface (SPI) camera developed to give the Arduino optical on board capabilities. [47] Its transceiver system is composed of four UHF deployable circularly polarized antennas that uplink and downlink information at 437.3 MHz and a radio board. It has an On-Board Data Handling (OBDH) subsystem and an On-Board Computer (OBC) that allows it to perform tasks such as Attitude Determination and Orbit Control (ADOC); scheduling and planning on the spacecraft. [48] It has been equipped with a momentum wheel that provides 1KUNS-PF with the ability to control its attitude and stability. [49] It also possesses an, Electric Power System (EPS) that regulates power to the different subsystems located in the satellite using Lithium Ion batteries and solar power. [50] These various subsystems are housed in a 1U CubeSat with miscellaneous structural pieces such as a NanoUtil top board. Figure 1.21 shows the elements in a stack and disassembled fashion. The communication architecture of 1KUNS-PF is shown in Figure 1.22.

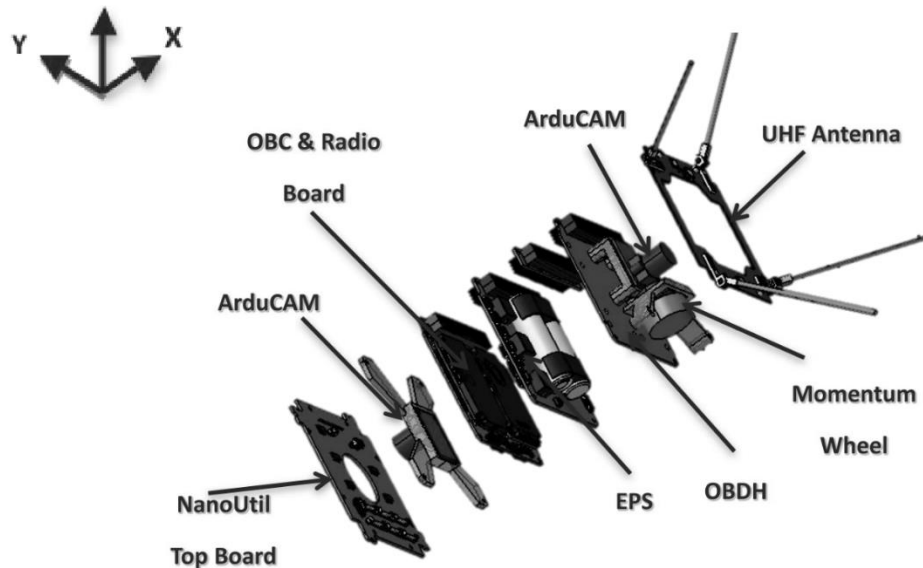


Figure 1. 20 Exploded view of 1KUNS-PF. [44]

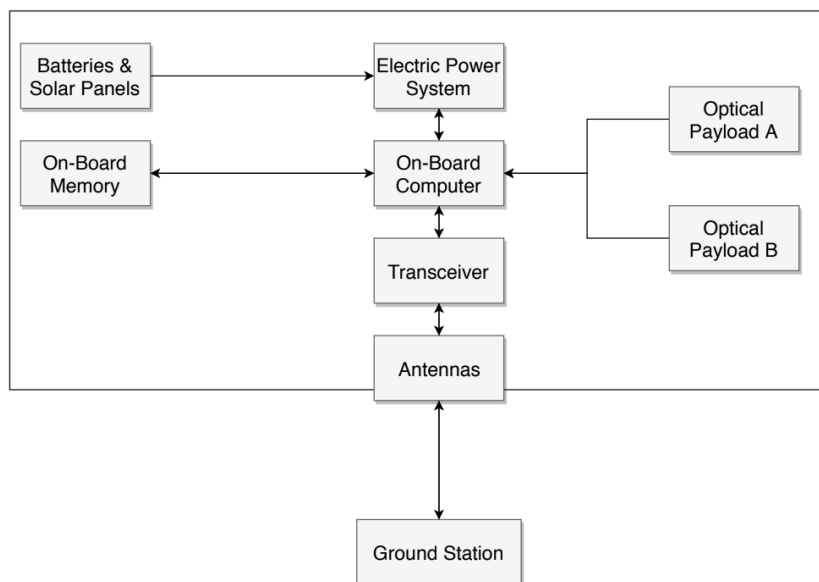


Figure 1. 21 Communication architecture of 1KUNS-PF. [44]

1.4 Communications

This section describes how a typical satellite communicates with an Earth ground station and then it will proceed to list and briefly describe some of the factors that may influence satellite to ground communication in LEO. This list is not exhaustive but was compiled to demonstrate that communication can be disrupted by a number of causes.

1.4.1 Satellite to Earth Communication

Satellites in orbit generally gather two types of information. The first type of information falls under the heading “Housekeeping”. Housekeeping refers to areas such as the health, safety, pointing position, temperature, and other status information of the satellite. This type of information is valuable to ground crews associated with

the operation of satellites because they can establish whether the satellite is working properly. The second type of information can be encompassed under the heading, “Mission data”. Mission data encapsulates information acquired through a satellite’s sensors for instance images, spectra and count rates. This information is generally sent to the ground for further processing by scientists and other interested parties. [51]

Now that the two main types of information are defined it is important to know how satellites store information and how and when they downlink information to Earth. Downlinking is dependent on a number of circumstances, so each satellite will have its own predefined system. Information can be stored and then forwarded to Earth once every orbit; once a day; as often as possible or in some cases in near real time for certain time critical applications. In terms of storage, satellites traditionally used to store information on magnetic tapes because they were reliable and could protect the integrity of satellite’s acquired information from factors such as cosmic rays, radiation and solar winds. Since there is always a probability for something to malfunction regardless of the memory storage system, precautions such as redundancy and checks are added and used to verify information. In terms of solid-state memory, seeing that it is the common system used nowadays, there are two main event groups that can jeopardize its integrity.

The first event group is the single event effects caused by a single energetic particle and it comprises three different types of events, namely a: [52]

- Single event upset (SEU)
- Single event latch-up (SEL)
- Single event burnout (SEB)

Collectively they produce what is referred to as single event effects (SEE). [52]

SEU

SEU’s were originally hypothesized by Wallmark and Marcus in 1962, and are defined by NASA as, “radiation-induced errors in microelectronic circuits caused when charged particles (usually from the radiation belts or from cosmic rays) lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs”. They are known as transient soft errors and regarded as non-damaging errors because if a SEU occurs in a device the device only needs to be reset or rewritten to restore standard behaviour. In memory they normally appear as bit flips. SEUs also have effects on analogue, digital, optical components and other surrounding interfacing circuitry. [52]

Multiple-bit SEU occur when a single ion hits two or more bits causing concurrent errors. It is easy to figure out that the data has been corrupted but the solution to the error is not straightforward. However, implementing precautionary measures in a solid-state memory system can solve or mitigate the risks involved with data corruption. Multiple-bit SEU errors affect single-bit error detection and correction (EDAC) in DRAM and certain types of SRAM because it is virtually impossible to designate bits in a word to several chips. [52] Figure 1.23 displays the best case; single event upset, and double or multiple event upset in a situation where Source A is meant to send Source B a seven-digit number.

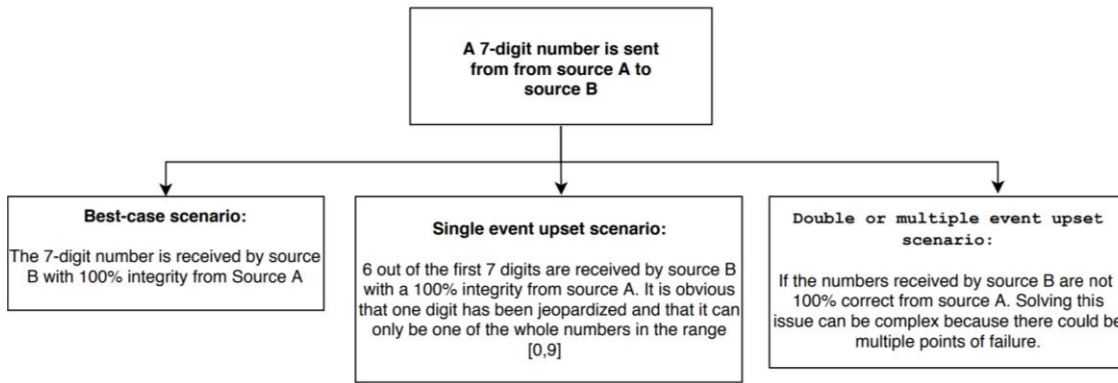


Figure 1. 22 An example of a single and double or multiple event-upset. [51]

SEL

A SEL, first witnessed by Kolasinski et al. 1979, is an event caused by a single-event induced current state that results in losses in the functionality of a device. They are caused by ions or by protons in certain components. They are regarded as hard errors because their effects sometimes have lasting destructive consequences. Due to the fact that SELs are caused by a high induced current inconsistent with the component it occurs in, it has the power to damage the component or to influence its receiving voltage and power supply. SELs can be cleared by through power rebooting or by power strobing. They are time sensitive events and they need to be rectified timeously to avoid catastrophic and lasting effects attributed to unwarranted heat, metallization or bond wire failure. [52]

SEB

A SEB a hard failure, originally described by Waskiewicz et al. in 1986, is a permanently destructive event caused by high currents in a power transistor. They have the ability to cause gate ruptures; MOSFET burnout; frozen bits and noise in charge-coupled devices (CCDs). In a power MOSFET if heavy ions were to pass through it depositing sufficient amounts of charge to power on the device a SEB may occur if it is biased in its OFF state. SEBs are less common in rising temperatures. A power MOSFET may also experience a single-event gate rupture (SEGR), first recorded by Fischer in 1987, when a conducting path is formed in the gate oxide causing a damaging burnout. SEBs also occur in Bipolar junction transistors (BJTs), first recorded by Titus et al. in 1991, and single-event dielectric ruptures (SEDRs), postulated by Swift et al, which has similar effects to that experienced by SEGR MOSFETs. [52]

All the SEEs discussed above are organised in Figure 1.23

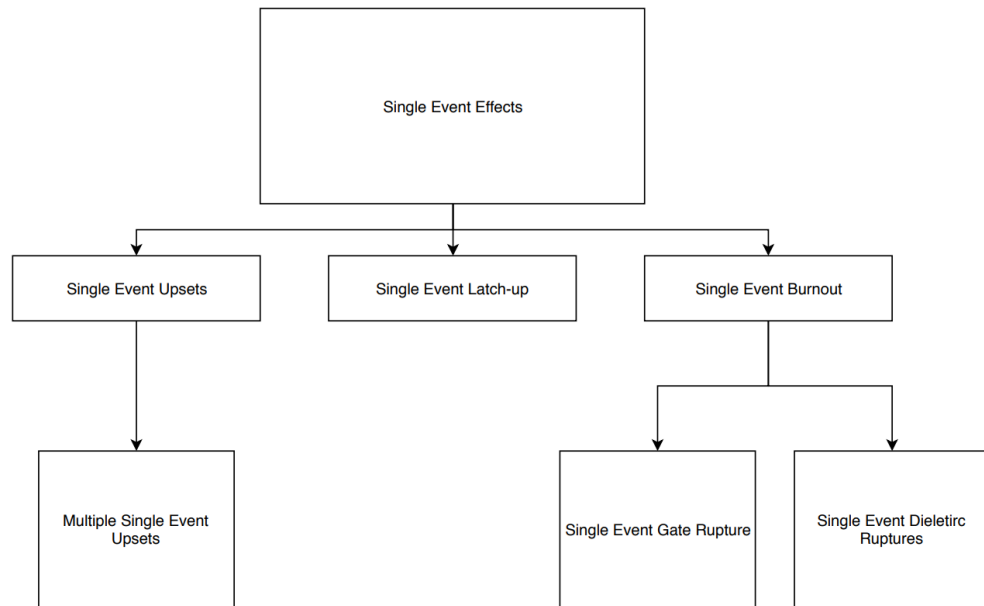


Figure 1. 23 A compilation of SEEs.

Once information is stored in a system and its downlinking times are set it needs to actually downlink the information to Earth. Information can be downlinked to Earth by using an intricate relay system or a simple single ground station. In this dissertation the use of a single ground station is of importance, so downlinking information in this way will be explained. In order to get a holistic picture of the process it is important to look at the satellite's transmitting antenna first. If a satellite is said to have a low-gain antenna, then its antenna does not require accurate pointing and the information downlink speed is slower as compared to a high-gain antenna. A high-gain antenna requires accurate pointing and as alluded to above transmits information at a faster rate as compared to a low-gain antenna. Many satellites use a combination of low and high-gain antennas. Low-gain antennas are generally used during the launch phase prior to deploying a satellite's high-gain antenna. Another reason to have two antennas on board a satellite is for redundancy in case of failure. A satellite's antenna sends information to an Earth receiving station at specific radio frequencies. The receiving Earth antenna should be tuned to the specific radio frequency used to transmit these radio signals. Antenna characteristics outlined in 1.2.2 also need to be considered when trying to receive data from a satellite. Once the signal has been received at the antenna it can be relayed through coaxial cables to be processed through amplifiers and computer signal processing and hardware and software. [51]

1.4.2 Satellite-to-Earth Communication Factors

Satellites in LEO have an orbital period of approximately 90 minutes. In view of this, a station that wants to receive data from a small satellite in LEO must consider the fact that the satellite is moving at a velocity faster than the Earth's rotational velocity. This ultimately means that the footprint of a satellite located in LEO continually shifts on the Earth's surface over time as opposed to a satellite located in Geostationary Orbit. A satellite's footprint is a region located on the Earth's surface where a receiver or sending device such as an antenna can downlink or uplink information from and to the

satellite.[53]. It is a function of the satellite's orbit; its transponder's beam shape and size and its distance from the Earth. [54] A footprint is normally shown visually on interactive maps as a lit-up area, as shown in Figure 1.24, taken from an open source software program called SatPC32. The white cross in Figure 1.24 represents a small satellite moving over the Mediterranean Sea with a footprint that spans across three continents, namely Africa, Europe and Asia. The white arrow pointing towards the North-East in Figure 1.24 just above the cross depicts the direction in which the satellite will travel as time moves on.

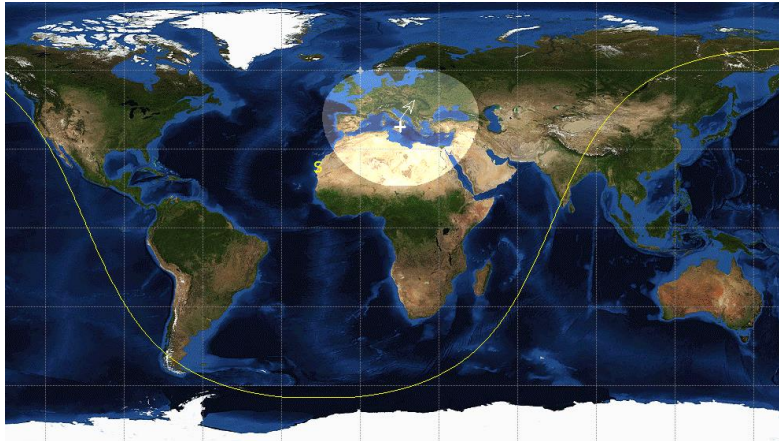


Figure 1. 24 An image of a small satellite's footprint on SatPC32 (2018/06/08).

If a directional antenna is used to receive data from a satellite in LEO, having a tracking system to follow the satellite is essential to allow the antenna to follow the satellite and downlink data from it for a longer period of time as opposed to a stationary directional or omnidirectional antenna. One can also consider deploying a system that predicts when the satellite will be in view of a certain antenna. This will allow the ground station to be used efficiently at finite times and to only receive and store the information it requires.

An antenna's positioning above sea level will also influence how it can receive data. A ground station located in a valley and surrounded by high peaked mountains will struggle to make contact with a low-powered small satellite as opposed to a ground station located on high ground with no physical obstructions that might obstruct the antenna's line of sight to the satellite. In addition to this, positioning an antenna in close proximity with electrical appliances may lead to signal loss and increased noise or interference. It is also difficult to account for the amount of signal loss in an internally housed antenna as opposed to an externally positioned antenna. Such factors are worthy to note when operating in amateur bands such as VHF and UHF because they are naturally susceptible to signal loss. [55]

Weather conditions in Earth's atmosphere can affect how fast a signal is sent or received and its integrity. Radio signals propagate at the speed of light when in a vacuum, however when they propagate through substances such as plasma, located in the ionosphere, radio signals can be influenced by delays; phase advance and attenuation. Mitigation tactics can be put into place to address these space weather phenomena but there is always the chance that such mitigation measures may not work and that could lead to severe information loss. [56] Within Earth's lower atmosphere weather occurrences such as light rain may not affect satellite-to-Earth communication

at all, however there are cases where storms, snow, tornadoes and hurricanes have affected satellite-to-Earth communication due to their intense nature. [57]

Again, these are just some issues involved between satellite and Earth communication. They are good to keep in mind when designing a ground station to communicate with small satellites in LEO.

1.5 Dissertation Structure

The rest of this dissertation follows the following structure. Chapter 2, Software Defined Radio Ground Station, discusses issues pertaining to elements involved with signal acquisition and processing in a SDR ground station. Chapter 3, Requirements Analysis, lists the mission's objectives, requirements and constraints. Chapter 4, Methodology, describes the SDR ground station's design process. Chapter 5, Commissioning Tests and Results, presents tests conducted to commission the SDR ground station and their results. Lastly chapter 6, Conclusions and Recommendations, presents conclusions regarding the whole body of work and recommendations for future work.

2 SOFTWARE-DEFINED RADIO GROUND STATIONS

Signal acquisition and signal processing elements that could be found in a typical SDR ground station will be discussed in this chapter. This chapter is split into two main sections, namely: 2.1 Signal Acquisition and 2.2 Signal Processing.

2.1 Signal Acquisition

The signal acquisition hardware chain in a satellite ground station consists of the antenna, rotator, rotator control box, rotator interface and LNA. The antenna's position is governed by the rotator, which is in turn controlled by the rotator control box that is controlled by the rotator control interface system linked to a computer. A signal enters an SDR ground station through its antenna. It then flows into and through a low noise amplifier, a device that starts the signal processing section, discussed in 2.2, in a typical SDR ground station. The signal acquisition process is described in the sub-sections below.

2.1.1 Antenna

An antenna can either radiate power or receive power. Regardless of its mode, when it is connected through a transmission line, a conductor which is suited to conducting current over different distances with a minimum amount of loss, to a ground station's inner circuitry, further signal processing can be done. A transmission line determines an antenna's function. If a straight transmission line, with infinite extent, is connected to an antenna that is conducting current at a uniform velocity then the antenna will not radiate power. [58] An antenna will radiate power in all of the following cases:

- If the current is being conducted at a uniform velocity and the transmission line is bent, truncated or terminated. [58]
- If the current being conducted in the transmission line accelerates or decelerates with respect to a varying time constant, regardless of whether the transmission line is straight or not. [58]
- If a waveguide, shown in Figure 2.1, is bent or terminated. A waveguide, a hollow metal tube, is a particular type of transmission line whose wall provides

a distributed inductance and whose hollow section provides a distributed capacitance. [58], [59]

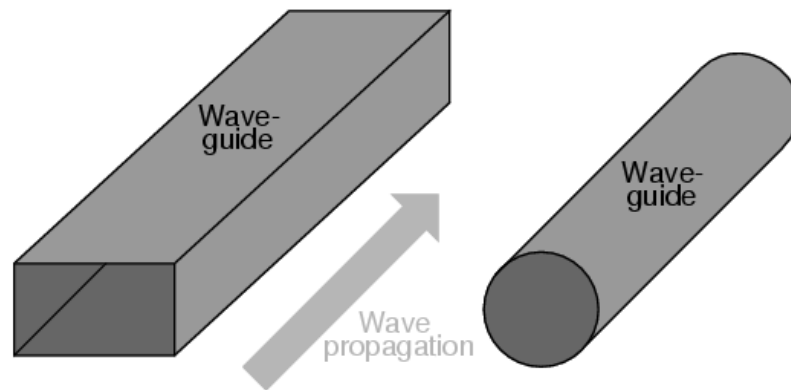


Figure 2. 1 An example of a waveguide. [59]

Figure 2.2 displays a waveguide which works as an antenna. The waveguide has an aperture that allows it to radiate energy, so that when power travels through the transmission line and into the waveguide that power is radiated thereby mimicking an antenna. [58]

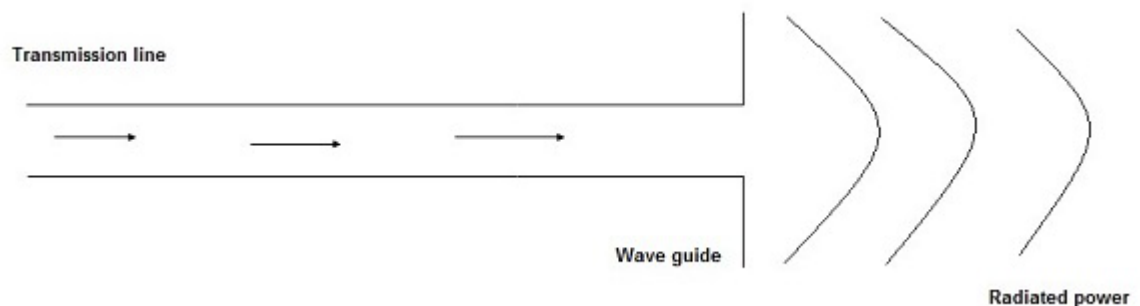


Figure 2. 2 A waveguide which works as an antenna. [58]

Antennas can be classified into three different groups based on their physical structure, mode of application and frequency range. An example of a structurally classified antenna would be a wire antenna. Wire antennas or random wire antennas are radio antennas that are constructed from an elongated wire positioned above the ground and whose receiver or transmitter is connected to ground. The length of the wire is not dependent on the radio's wavelength and they are consequently not as effective when compared to antennas that are dependent their radio's wavelength. The wire can be straight or bent, in which case it is referred to as a zigzag antenna, as shown in Figure 2.3. Wire antennas are monopole antennas. They are normally used to receive or transmit in long, medium and short-wave bands.



Figure 2. 3 An example of a zigzag antenna. [60]

An example of a mode application antenna would be a radar antenna. [58]. Ground penetrating radar antennas are able to create and detect significant EM waves. Antennas involved with the transmission of radar waves must be able to transform excitation voltages into temporal and spatial distributed fields that are predictable. On the other hand, antennas involved in radar reception need to be able to sense EM temporal variations of vector components and transform them into recordable signals. The list below describes the characteristics that are vital for radar antennas: [61]

- Precise source and detection sites must be identifiable.
- Responses from transmitters and receivers, which involve converting electric field transfer functions to voltages and the reverse, need to be invariant of time and space.
- A vector character of a field that links the source voltage and received voltage must be measurable.
- A system's application needs should correspond to an antenna's bandwidth.

The characteristics listed above are not trivial to achieve because finite sized antennas are required to efficiently generate and detect EM fields. In addition to that, the time taken for current to move across an antenna's full dimension needs to be similar to the rate of temporal change of an excited voltage field. Figure 2.4 shows examples of radar arrays: (a) is a large parabolic antenna, situated in Erdfunkstelle Raisting, used to communicate with satellites and (b) is a radar installation operated by the United States Federal Aviation Administration (FAA).

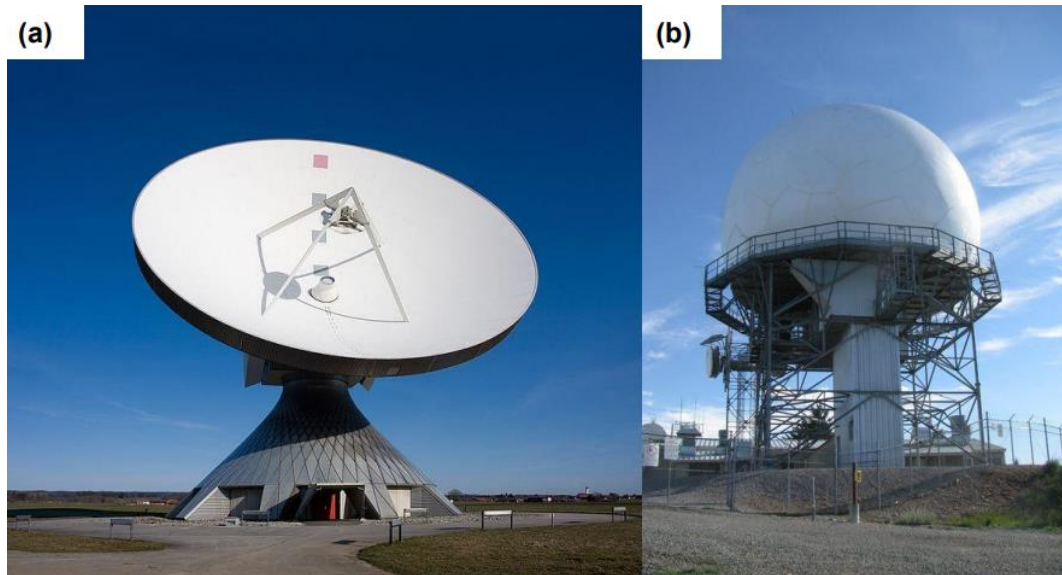


Figure 2. 4 Two examples of radar antennas (a) a parabolic and (b) a dome covered antenna. [62], [63]

An example of a group of antennas that are described in terms of their frequency are UHF antennas, radio antennas of interest to this dissertation. A radio antenna is a transducer that is able to transform radio frequency (RF) fields into alternating current (AC) or the reverse, making it possible for them to transmit or receive RF signals. The antennas are made up of metallic conductors that are connected to radio transmitters or receivers electrically. Radio antennas are a vital component when it comes to operating radio equipment. UHF antennas operate in the range of 300 MHz to 3 GHz. Their wavelengths range from 1m to one tenth of a metre, so UHF is also referred to as the decimetre band. The length of a UHF antenna is related to its radio waves. UHF waves are inherently short, therefore UHF antennas are generally described as stubby and short. For example, a quarter-wave monopole, shown in Figure 2.5, can range between 2.5 cm to 25 cm in length. UHF radio waves mostly propagate by line of sight, so large features such as hills generally block UHF radio wave propagation. However, UHF wave transmission through building walls is generally strong enough for indoor reception.

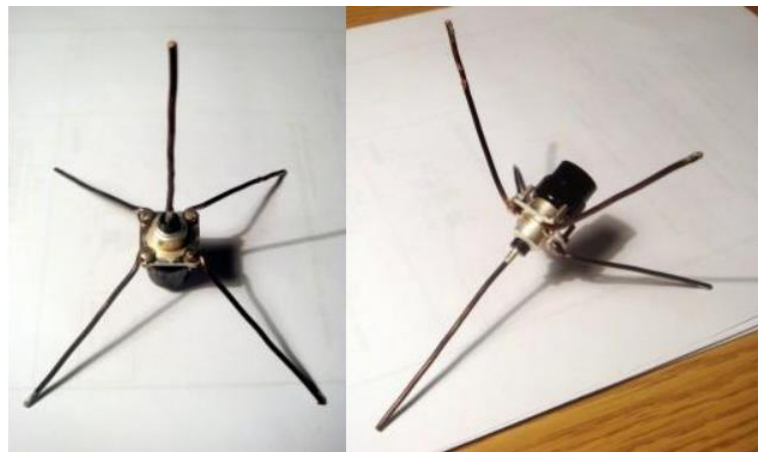


Figure 2. 5 A quarter-wave monopole antenna. [64]

UHF antennas are used for a number of applications that include television broadcasting, cell phones, satellite communication and Bluetooth. In terms of satellite communication, antennas such as a helical and turnstile, both shown in Figure 2.6, are used because a large number of satellites, especially small satellites, have circularly polarized antennas that are not sensitive to the relative orientation of a ground station's receiving or transmitting antenna.

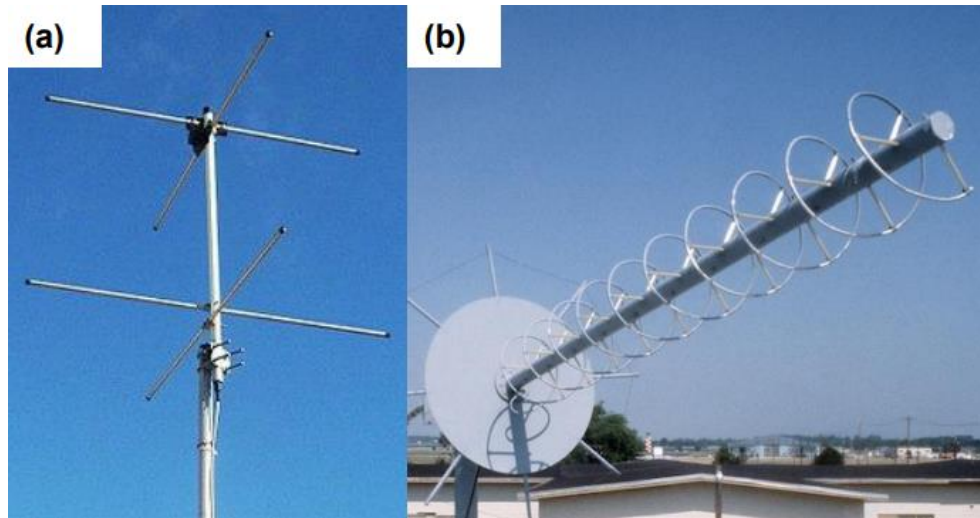


Figure 2. 6 A (a) turnstile and (b) helical antenna.[65], [66]

For an antenna to pick up an appropriate radio wave it needs to be calibrated to detect and receive a certain type of RF. [67] An antenna that has been constructed to receive signals cannot, without calibration, transmit signals into outer space [68]. To adhere to national and international regulations, it is very important that an antenna works within its designated operational frequencies to avoid radio spectrum misconduct.

2.1.2 Rotator

The antenna rotator can be divided into three parts: hardware, control box and interface. For this reason, they will be described separately to show how they work together, yet accomplish separate tasks.

2.1.2.1 Hardware

Physically, the hardware of an antenna rotator can differ from system to system. For instance, some rotators have hardware that provide horizontal (azimuth) movement, vertical (elevation) movement, or a combination of the two. In general, the hardware of an antenna rotator allows one to track a satellite as it moves over an antenna's horizon. Deciding upon which antenna rotator to use is dependent on what needs to be tracked. Signals from small satellites in LEO, with ever moving footprints, can be acquired without using a rotator. However, a rotator is helpful because it makes it easier to track a satellite's signal more accurately as opposed constantly having to adjust an antenna's pointing direction manually to keep up with the satellite's footprint during transmission.

An antenna is normally attached to a rotator, regardless of its capabilities, through a boom otherwise known as a cross-bar. Figure 2.7 provides examples of how an antenna can be attached to a cross-bar and then to a rotator if the rotator has azimuth, elevation or azimuth and elevation capabilities. The examples provided are not exhaustive.

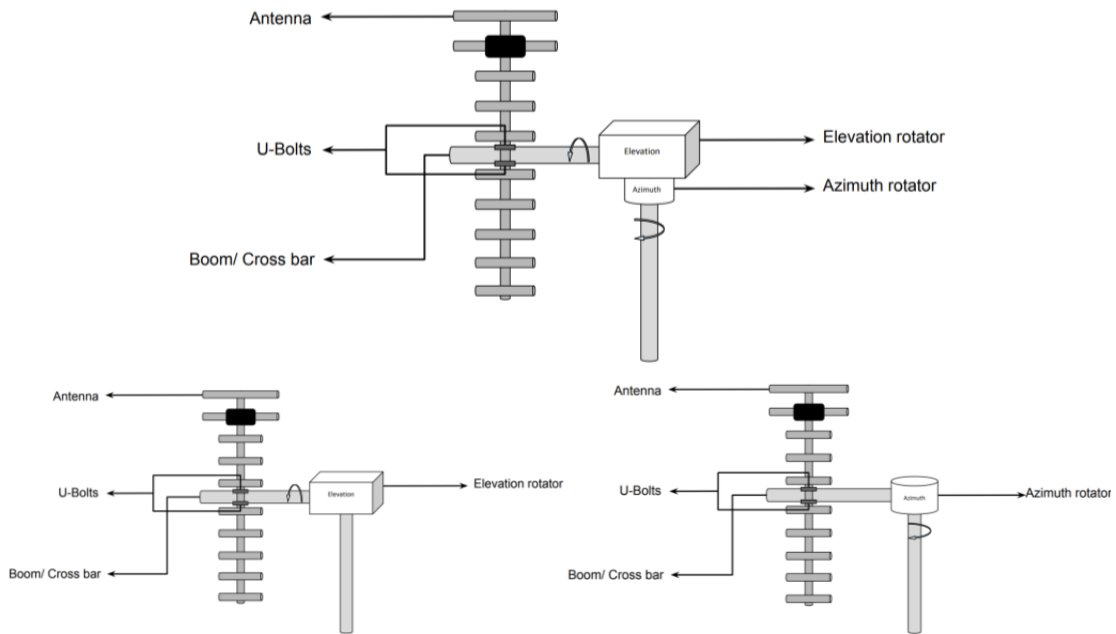


Figure 2. 7 Different rotator configurations.

The azimuth-and-elevation capable rotator is good for tracking small satellites in LEO since their positions change constantly over time. An azimuth-only rotator is good for tracking objects with low elevations and an elevation-only antenna is suited to tracking objects in low near-polar orbits.

2.1.2.2 Control Box

A rotator's control box is a physical element normally connected directly to a rotator's hardware. A rotator's position is primarily, in the case when it is not automatically controlled by external software, manually manipulated with a control box's azimuth and or elevation switch or switches. Azimuth and elevation movements are normally measured in degrees within a stipulated range. Some rotator control boxes also include cardinal directions with respect to the azimuth plane to show the operator which direction their antenna is pointing towards.

In terms of tracking small satellites in LEO, using the control box manually means that the user needs to be in constant contact with the control box to successfully track the satellite under investigation. The user would also have to know, beforehand, the trajectory of the satellite with relation to their antenna. If the antenna is meant to only receive signals in one plane, manual operation could work, however if the satellite moves significantly in both elevation and azimuth planes, as most small satellites in LEO do, then manual operation is not practical. In such cases it would be better to automate the control box with an interface controlled by a computer. The following section, "Interface and Computer", discusses this.

2.1.2.3 Interface and Computer

A rotator's interface is a device that is placed between the rotator control box and a computer, as shown in the block diagram in Figure 2.8. The interface and the computer are discussed jointly in this section because they are closely related.

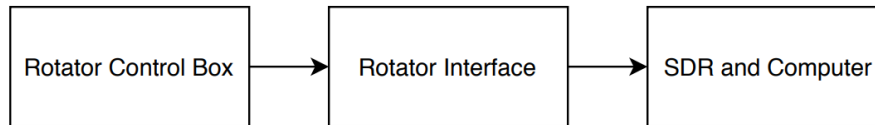


Figure 2. 8 Shows the positioning with respect to the rotator control box and the Computer.

To track a satellite automatically it is vital to know its orbital attributes. This can be found on numerous websites, texts and using widely available software. Once that is acquired, one needs to figure out where the satellite is and where it will be over time. This too, can be found using online resources such as N2YO.com and STK. When its name and predicted locations are available and accessible, that information needs to be linked to a commercial or microcontroller-based rotator interface. Commercial interfaces are normally pre-programmed devices that, when linked with the appropriate software, can track a satellite's movement. Some commercial interfaces have proprietary software, and this can limit their flexibility. To save on financial costs associated with building a ground station, one can develop a custom rotator interface using a microcontroller such as a Raspberry Pi or Arduino. Developing a microcontroller-based interface might involve setting up on-board or off-board circuits as well as software. This approach could be cumbersome, because of the additional work required to set up the interface. However, the developer has the power to create a unique rotator interface adapted to their needs. Finally, regardless of architecture, the interface needs to be attached to a control box to send and receive information to control the rotator's movement. A great amount of precision is introduced when an interface is used because it is able to adjust the rotator's position in small increments that would be hard for a human to accomplish manually. It also has an added advantage in that it is able to move in the azimuth and elevation planes simultaneously, which would be inefficient if a human were to try and mimic the same behaviour. This saves time and allows the antenna to ultimately capture signals over a longer period for the ground station to process.

2.2 Signal Processing

Signal processing deals with the manipulation of the signals transmitted into the SDR ground station through the antenna with the help from rotator related elements. In a typical SDR ground station setup a signal is transported through a transmission line to a LNA where it can be amplified. From the LNA it travels to a SDR where the signal can then be displayed and processed on a computer in order to decode or view and assess its waveform. The signal processing section of a SDR ground station is discussed below.

2.2.1 Low Noise Amplifier

A Low Noise Amplifier (LNA), in terms of an antenna receiving RF signals, can be described as a two-port electronic device that takes in a radio signal through one port, call it the input port, and amplifies the signal so that at the second port, the output port, the signal exhibits an amplified amplitude and/or power [69]–[73]. Figure 2.9 displays a schematic diagram of an LNA with reference to an antenna and a receiving radio, in this case an SDR. Designing an LNA is not a trivial task because it has to attempt to account for unknown signals with unknown sources of noise, one of the most challenging signal processing concepts [74].

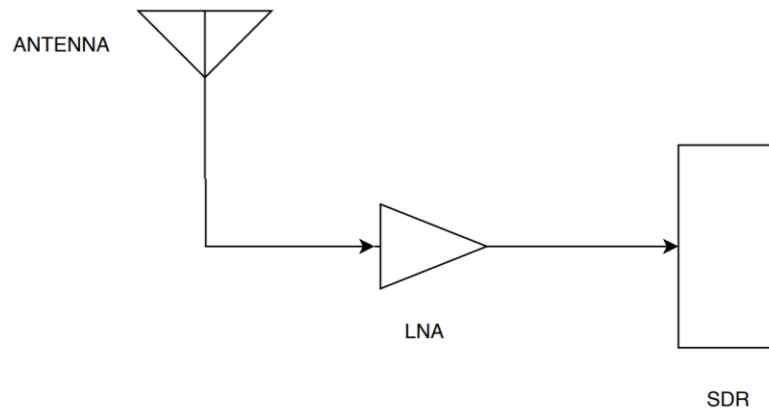


Figure 2. 9 A LNA schematic in relation to a SDR and an antenna.

A LNA is particularly useful for signals with low voltages, low power and noise. Noise contributions arise in the different mediums and various elements through which the signal travels. [69], [74]. Once a signal has gone through a LNA, the output signal should be more usable for further processing as compared to the input signal [69], [75].

The most important parameters associated with an LNA are Noise Figure (NF), gain, linearity and impedance matching. NF can come from thermal sources and from the LNA itself. [74], [75] Gain is related the capacity of the LNA to increase the amplitude or power of the received signal [70]–[74]. Linearity in an ideal LNA means that the output signal strength and the input signal strength are directly proportional. [76]. In an ideal linear device, the amplitude or power ratio between the output-to-input signal is uniform, as long as the power of the input signal is not considerably large. In such a case where the input power is strong, a LNA with linear characteristics will exhibit non-linear characteristics. This problematic and common phenomenon is known as overdrive. [76], [77] Lastly, impedance matching in an LNA deals with matching the signal's impedance to the internal impedance of the LNA to achieve favourable LNA characteristics [75], [78].

2.2.2 SDR and Computers

Historically, radios were developed to analyse distinct waveforms. A radio is a device that is capable of receiving and/or transmitting information wirelessly within the Radio Frequency (RF) band. It is relatively simple to build an optimum radio, where

performance, size and power are all factored in, if it is intended for one specific waveform and purpose. However advantageous it is to have a device that is heavily optimised to suit a specific task, having an unadaptable radio can be a disadvantage because it means that one needs to create a new device for every task, which is costly. SDRs differ from traditional radios in that they can inherently support different waveforms and are known as multi-functional devices. [79] There is no universally recognised definition of a SDR, but the Institute of Electrical and Electronic Engineers (IEEE) “P1900.1” describes a SDR as being, “A type of radio in which some or all of the physical layer functions are software defined.” [80], [81] The same IEEE working group “P1900.1” also stated that for a radio to be a SDR its needs to house software or firmware that is modifiable, “post deployment”. The physical layer mentioned in the definition refers to level one of the Open Systems Interconnection (OSI) model as represented in Table 2.1, adapted from, “Implementing Software Defined Radio”, by Eugene Grayver.[79] Signal mixing, filtering, amplifying, modulating, demodulating, coding, processing and detection are some of the inherently hardware, physical layer, tasks that a SDR can implement in software.[82], [83]

Table 2. 1 Open System Interconnection layers. [79]

Layer Type	Data Unit	#	Name	Function
Host Layers	Data	7	Application	Network process to application
		6	Presentation	Data representation and encryption
		5	Session	Inter-host communication
	Segment	4	Transport	End-to-end connections and reliability
Media Layers	Packet	3	Network	Path determination, logical addressing
	Frame	2	Data Link	Physical addressing
	Bit	1	Physical Layer	Media, signal, and binary transmission

A SDR, just like a traditional radio, can be used in signal transmission, reception or a combination of the two. [82] In the context of this dissertation, receive-only SDRs were relevant because this dissertation aimed to produce a receive-only SDR ground station. As a reminder from Chapter 1, a receive-only station does not require a radio license, although a ground station with transmitting capabilities does.

The introduction of SDRs does not negate traditional hardware, but they are advantageous because of some of the following reasons listed below: [80], [82], [83]

- Experimental – Provides one with the ability to scrutinize multiple RF signals by performing diverse techniques on them, such as modulation and decoding. [82]
- Availability – Some SDRs can be purchased for approximately R300, such as the RTLSDR RTL2832U DVB-T Tuner Dongle. [84]
- Extendible and Novel– Can be upgraded using software downloads and there is also freedom to create new features that are not included in the original device.

Additionally, some tasks that are unable to be implemented in hardware, due to physical constraints, can be implemented in software. [81]–[83]

- Efficient – Commercially produced SDRs similar to the RTLSDR RTL2832U DVB-T Tuner Dongle can run on 4.5-5V through a USB connection. Some SDRs are also equipped with bias tee circuits that can power other devices such as LNAs [84]

Security concerns are an evident topic in the SDR community and form a separate group of research. Since one way in which SDRs can be updated is through software downloads, they are susceptible to an array of malicious attacks masked as legitimate downloads [83], [85]. Software downloads are not limited to downloadable files over the internet, they include all downloads that happen through wireless media; wired media or through device peripherals [85]. In view of this issue, it is necessary for authentication and verification protocols to be implemented to protect those that create and those that use SDR downloadable software. Software that is developed or modified in a malicious or reckless manner could corrupt the device that is downloading it and other devices, knowingly or unknowingly. Corruption does not only encapsulate viruses but also software that modifies a device beyond its legal jurisdiction without following the necessary protocols. Issues regarding how to prevent the spread of malware and who should govern the authentication of software are some of the pertinent issues in the SDR community. [83], [85]

A computer helps download, install and instantiate software for a SDR. Computers also allow one to view and manipulate a received waveform in a receive-only SDR ground station. Many computer programs for small satellite packet-decoding are available on line at no cost. There are many open source and propriety Windows, Linux and Mac OS X SDR user interfaces that allow users with little knowledge of the software or RF intricacies to interact with their received data. Most of the platforms have a fair amount of documentation and access to community members for platform queries. Knowledge sharing is a big part of the amateur radio community and people are interested and eager to solve SDR-related problems in general.

In the next chapter we define the objectives, requirements and constraints for the SDR ground station developed in this distinction.

3 MISSION OBJECTIVES, REQUIREMENTS AND CONSTRAINTS

This short chapter presents the mission's qualitative objectives and quantitative requirements and constraints set out before we commence the development of the SDR ground station. The mission statement, found in the introductory chapter of this dissertation, gave rise to the qualitative objectives. The mission's requirements and constraints were then consequently established from the mission's objectives. Collectively, the objectives, requirements and constraints were constructed to guide the design process and validate the final SDR ground station. They are therefore referred to continually in successive chapters.

3.1 Qualitative Mission Objectives

There are three types of qualitative objectives observed in this dissertation. The list below presents and explains each objective type.

- Primary
 - Refers to what fundamentally needs to be accomplished for this mission to be successful.
- Secondary
 - Objectives that are alluded to in the mission statement and are dependent on the success of the primary objective being met. The mission would still be successful if the secondary objectives were not met.
- Hidden
 - Not necessarily explicitly stated in the mission statement. They are objectives that could possibly be realized because of the mission's characteristics. The mission would still be successful if the hidden objectives were not met.

Table 3.1 explains this dissertation's primary, secondary and hidden objectives

Table 3. 1 The mission's qualitative objectives.

Type	Objective
Primary	Design and build a low-cost, portable and expandable SDR ground station to receive physical satellite data such as packets and or CW audio from LEO small satellites operating in the 70-cm band.
Secondary	Data sharing.
	National and international cooperation.
	Participate and contribute to national/international projects.
	Support future SpaceLab missions.
Hidden	Highlight SpaceLab's capabilities.

3.2 Quantitative Mission Requirements and Constraints

The quantitative mission requirements and constraints are presented respectively in Tables 3.2 and Table 3.3. There are two types of requirements listed in Table 3.2 namely, functional and operational requirements. Functional and operational requirements are defined as:

- Functional - The system's capability
- Operational - Aspects that should be prevalent when the system is in use.

Each requirement in Table 3.2 was defined in order to define its boundaries and deliverables.

Table 3. 2 The mission's quantitative functional and operational requirements.

Requirement	Explanation
Functional	
Tracking	The system should be able to track one small satellite at a time.
Decode	The SDR ground station should be able to decode at least one type of the data (sound, packets) it receives into another form. For instance, audio into CW and packets into ASCII or Hex code.
Operational	
Tracking Interval	The SDR ground station should be able to track a satellite intermittently for a maximum of 3 minutes.
Frequency	The SDR ground station should be able to make contact with a satellite operating in the 70-cm band.
Orbit	Tracked satellites should be located in LEO.
Storage	The system should be able to store the information from the satellite for subsequent analysis and processing.

Table 3.3 presents the mission constraints. This table presents criteria used to design the SDR ground station in order for it to work in its intended manner within explicit boundaries.

Table 3. 3 The mission's quantitative constraints.

Constraint	Explanation
Cost	The total cost of the SDR ground station should be R20000 or less.
Schedule	The SDR ground station should be operational within one year.
Regulations	No uplink capabilities
Interfaces	All control interfaces of the SDR ground station should be able to be operated by one computer.
Environment	The SDR ground station should be rated to withstand a wind speed of $5m \cdot s^{-1}$ at its centre of mass.
Portability/ Weight	The system should have a mass of less than 50 kg. (Excluding computers)
Automation	Tracking should be automated.
Height	The SDR ground station should be under 2m in height when its antenna is in its azimuth plane with zero elevation.
Power	The SDR ground station should only utilize equipment rated at 230 V / 50 Hz or lower.

4 SYSTEM DESIGN

The processes followed to conceptualize and design the SDR ground station are discussed in this chapter. The mission's objectives, requirements and constraints, outlined in Chapter 3, considerably influenced the design process as described in this chapter. To construct the final SDR ground station three main activities were conducted. Each activity is listed and described below.

4.1 System design

An iterative design process was used to incrementally conceptualize what main elements the SDR ground station needed. Four designs were conceptualized to produce the final design. To methodically produce the final design, the advantages and disadvantages of each design were recorded so that they could be addressed in successive design iterations. Each design is presented together with a table listing its notable advantages and disadvantages. In order to identify which disadvantages were acceptable and unacceptable to the SDR ground station's mission, two columns exist in each table called, "State", and "Reason". If the disadvantage was regarded as acceptable it has a letter "A", and if it was unacceptable it has a letter "U", next to it. The "Reason" column explains why each disadvantage was chosen to be acceptable or unacceptable.

As mentioned before, the mission's objectives, requirements and constraints were continually considered throughout the conceptual design process. When they were reviewed, it was decided that the following requirements, listed below, were important to:

- The SDR ground station had to be portable.
- The SDR ground station had to be cost effective.
- The SDR ground station had to be expandable.
- The SDR ground station had to operate in the 70-cm band

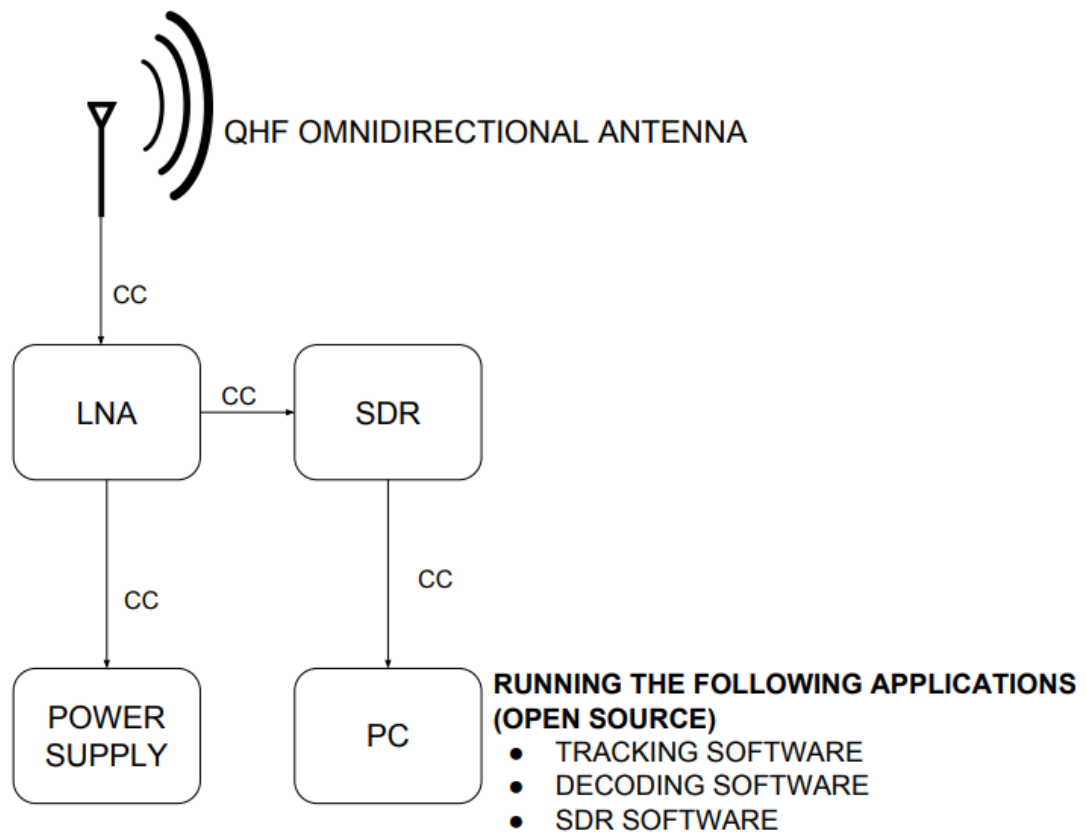
Four conceptual design iterations were considered and evaluated against the following criteria:

1. The final design can only have acceptable disadvantages.

2. The final design meets the following factors associated with the mission's objectives, requirements and constraints:
 - a. The final design produced needs to be portable.
 - b. The final design produced needs to be cost effective.
 - c. The final design produced needs to be expandable.
 - d. The final design produced needs to conceptually allow the SDR ground station to operate in the 70cm band.

The first design, shown as a block diagram in Figure 4.1, was taken from a Power Point presentation entitled, "Building a Simple Satellite and CubeSat Ground Station", given by Bob and Jann Koepke. [86] Their design used the following items:

- an omnidirectional antenna (137 MHz)
- a LNA with a power source
- a SDR
- a PC



*CC - CONNECTION CABLE

Figure 4. 1 Bob and Jann Koepke's SDR ground station design. [86]

This design was inappropriate for this dissertation because it had two unacceptable disadvantages related to its antenna, as shown in Table 4.1. Therefore, the design process could not be concluded at this stage.

Table 4. 1 Design 1's features.

Area	Advantages	Disadvantages	State (A/U)	Reason
QHF antenna	QHF antenna has a simple design.	The omnidirectional antenna increases the chance of noise being picked up from multiple sources.	U	The additional noise will distract from the signal under investigation.
		Omnidirectional antenna cannot track a small satellite accurately.	U	The system needs to be able to track a satellite.
LNA	Noise reduction.			
Power source		Limits portability.	A	A battery can be used if wall power is not available.
SDR	Cost effective compared to traditional hardware-based radios.			
	Functionally diverse			
PC	Software is open source and free.			
General	The system is not bulky.			

From Table 4.1 a decision was taken to increase the likelihood of the system being portable by introducing a LNA with a bias-T LNA. These LNAs are powered through the coaxial cable connected from the antenna negating the need for a dedicated power supply. Design 2 is shown below in Figure 4.2

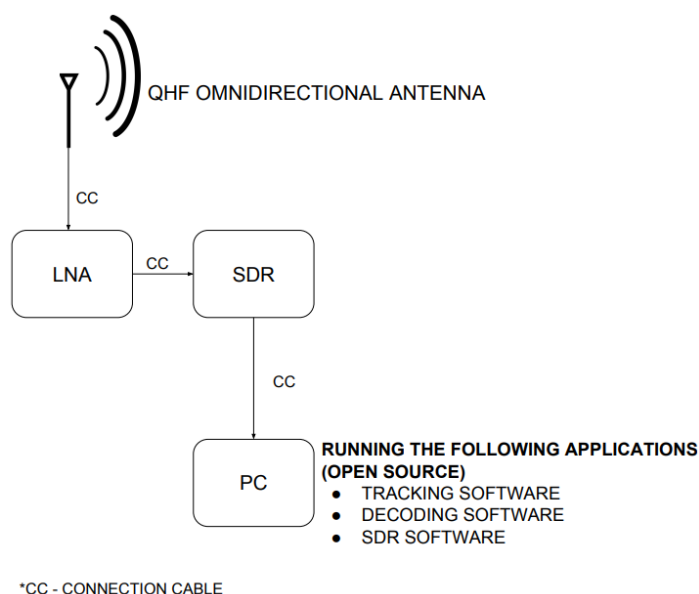


Figure 4. 2 Design 1 modified with a bias-T LNA to negate the need for a power source.

The total number of disadvantages decreased from three in Design 1 to two in Design 2, as shown in Table 4.2. However, both disadvantages were labelled to be unacceptable. For this reason, the design process was not concluded at this point.

Table 4. 2 Design 2's advantages and disadvantages.

Area	Advantages	Disadvantages	State (A/ U)	Reason
QHF antenna	QHF antenna has a simple design	The omnidirectional antenna increases the chance of noise being picked up from multiple sources.	U	The additional noise will distract from the signal under investigation.
		Omnidirectional antenna cannot track a small satellite accurately.	U	The system needs to be able to track a satellite.
LNA	Noise reduction.			
SDR	Cost effective compared to traditional hardware- based radios.			
	Functionally diverse.			
PC	Software is open source and free.			
General	System is more likely to be portable because the LNA doesn't require a power source anymore.			
	The system is not bulky.			

A feature that was prevalent in both Design 1 and 2 was the QHF antenna. The QHF antenna, originally featured in Bob and Jann Koepke's design, was manufactured to work at 137 MHz. This frequency was not acceptable for this thesis so Design 3, in Figure 4.3, addressed this issue by replacing the QHF antenna with a directional antenna operating in the 70-cm band (430 – 440 MHz). In addition to this, the third design also added in a rotator with azimuth and elevation capabilities, a rotator control box and a rotator interface. They were added to the ground station to allow the directional antenna to track small satellites in LEO, seeing that, the omnidirectional antenna did not possess that ability. A power source was also added into Design 3 to power up the control box. This was slightly disadvantageous because Design 2 negated the need for a power source. However, a power source does not fully stop the ground station from being portable. This addition was therefore recorded to be acceptable in Table 4.3 because a battery can be used in place of wall-socket power and extension cords can be used if wall power is available nearby but not directly at the location of the SDR ground station.

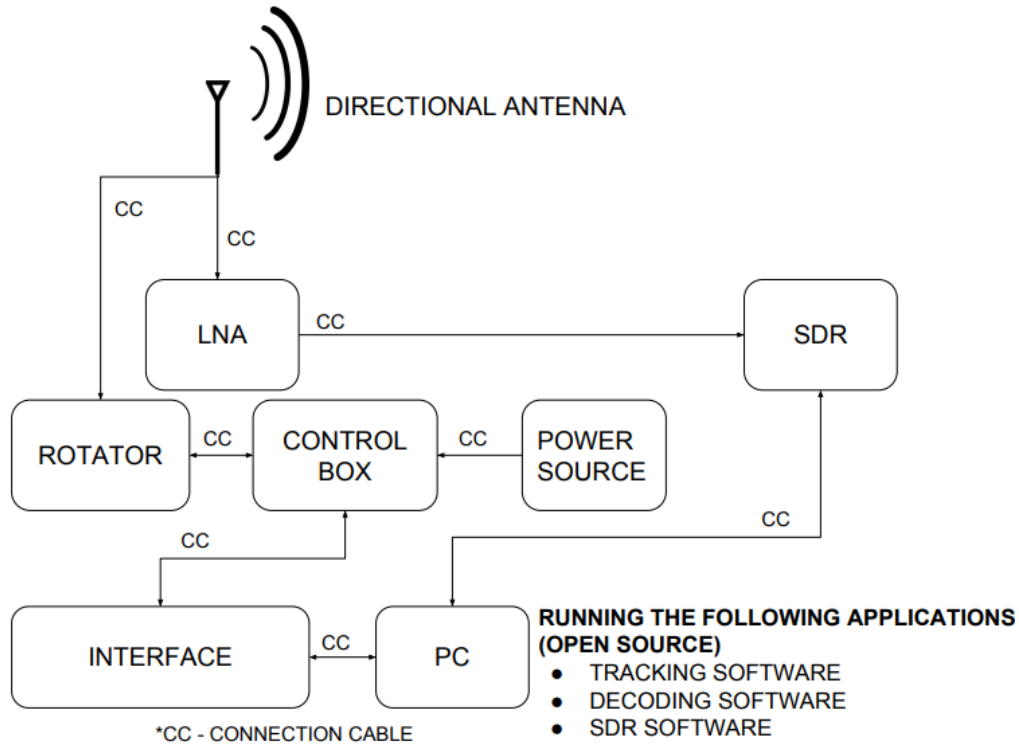


Figure 4. 3 Design 3 modified Design 2 to include a directional antenna, rotator, rotator controller a rotator controller interface.

The introduction of the rotator-related elements and the directional antenna increased the number of disadvantages recorded in Table 4.2 for Design 2, as shown in Table 4.3, however it decreased the number of unacceptable disadvantages from two in Design 2 to one in Design 3 namely, the costs associated with the rotator-related elements. In addition to this, established and trusted commercially developed rotators are known to be expensive, so this design was not suitable for this thesis because the ground station needed to be cost effective.

Table 4. 3 Design 3's advantages and disadvantages.

Area	Advantages	Disadvantages	State (A / U)	Reason
Directional antenna	Can track small satellites in LEO.			
	Operates in the 70-cm band.			
LNA	Noise reduction.			
SDR	Cost effective compared to traditional hardware-based radios.			
	Functionally diverse.			
PC	Software is open source and free.			
Commercial rotator	Contributes towards small satellite tracking.	Expensive pieces.	U	Collectively, the pieces could be very costly.
Commercial rotator controller				
Commercial rotator controller interface	User friendly interaction.	No customization. The interface is based on the supplier's decisions.	A	Customization is not essential.
	Rotator can be controlled from a computer.			
Power source		Limits portability.	A	A battery can be used if wall power is not available.
General	Not bulky.			

Design 4, shown in Figure 4.4, replaced the commercial rotator interface with a commercial general-purpose microcontroller to alleviate the high costs associated with the rotator-related elements. The microcontrollers, unlike the commercial rotator interfaces, are not plug-and-play devices. For them to function as a rotator interface they require configuration and it was noted that this could have direct implications on the project's timeline. In addition to replacing the rotator interface with a microcontroller, the LNA was removed from the system to also decrease the overall cost of the ground station. The LNA was initially included to amplify weak incoming signals, however it is not impossible to receive and decode signals that haven't been processed through an LNA.

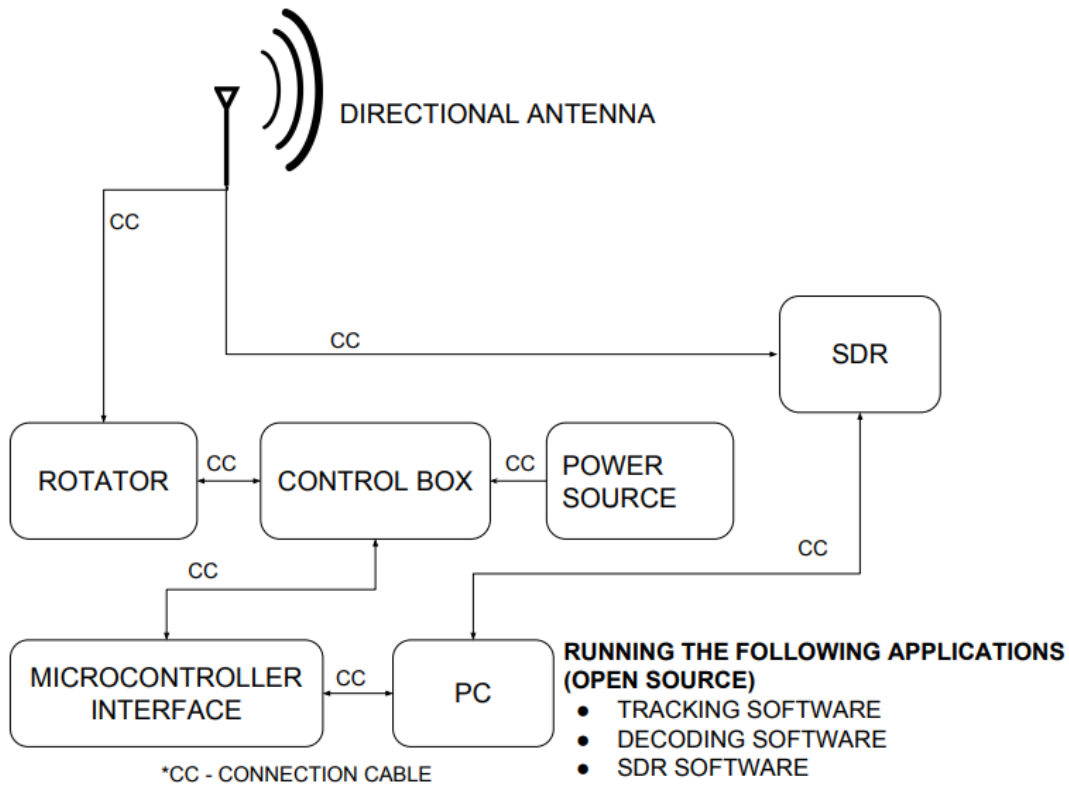


Figure 4. 4 Design 4 modified Design 3 by replacing the commercial rotator interface with a general-purpose microprocessor.

Table 4. 4 Design 4's feature table.

Area	Advantages	Disadvantages	State (U/ A)	Reason
Directional antenna	Can track small satellites in LEO			
	Operates in the 70-cm band.			
SDR	Cost effective compared to traditional hardware-based radios.			
	Functionally diverse.			
PC	Software is open source and free.			
Commercial rotator	Contributes towards small satellite tracking.	Expensive pieces.	A	The rotator controller has been removed from the total amount so the cost is more acceptable.
Commercial rotator controller				
Commercial microcontroller interface	The interface can be customized to suit the user and their needs.	Not a plug and play devices. Requires configuration based on need.	A	Requires more time and work however it is doable.
	Cost effective			
	Documentation freely available for most popular commercial microcontrollers.			
	Rotator can be controlled from a computer.			
Power source		Limits portability.	A	A battery can be used if wall power is not available.
General	Not bulky.	No LNA will weaken the strength of the incoming signal.	A	The system should still be able to pick receive and decode some signals.

The adjustments made in Design 4 subsequently, as reflected in Table 4.4, increased the total number of advantages and they also made all the disadvantages acceptable. In view of this, Design 4 was assessed against the criteria listed earlier. Table 4.5 shows how Design 4 measured against these criteria.

Table 4. 5 Design 4 weighed up against assessment criteria.

Criteria	Achieved	Reason
The final design can only have acceptable disadvantages.	Yes	Design 4 had four disadvantages and they were all classed as acceptable.
The final design produced needs to be portable.	Yes	Design has a power source, however this does not fully limit portability because a battery can be used in place of wall-socket power in remote locations. In addition to this, extension cables can be used if the wall-socket power available but not directly at the SDR ground station's position.
The final design produced needs to be cost effective.	Yes	A LNA and commercial rotator interface was removed to decrease overall SDR ground station costs.
The final design produced needs to be expandable.	Yes	Design 4 is not bulky and possesses devices that can be expanded upon.
The final design produced needs to conceptually allow the SDR ground station to operate in the 70-cm band	Yes	A 70-cm directed antenna was included in Design 4.

According to Table 4.5, Design 4 met all the criteria listed at the start of this chapter. Therefore, the conceptual design process for the ground station was concluded at this point.

5 DETAILED DESIGN, PARTS SELECTION AND ASSEMBLY

In Chapter 4 we discussed several iterations of the high-level conceptual design, settling finally on the conceptual design illustrated schematically in Figure 4.4. In this chapter we will translate that conceptual design into an embodiment design. As mentioned in Chapter 1, the development of the SDR ground station will make use of COTS components and open source software in order to contain development costs and development time. This entails making choices from among available COTS components for each of the subsystem components. These choices in turn will drive the further detailed design of the SDR ground station

5.1 Identification of suitable COTS components

Desk-top research was conducted on a wide range of potential COTS components. We took into consideration the intrinsic technical capabilities of each item, the cost, lead time for procurement, the actual use of such components in working systems, user reviews and comments about the various products, compatibility with products under consideration for other subsystems, ease of interfacing with other suppliers' products, and compatibility with open-source software.

Space does not permit us to reproduce here the extensive information that was obtained from this desktop research. Instead, we will focus on the items that were identified as being most appropriate for the present application.

In selecting the preferred components, we were guided by the criteria set out in the Mission Statement for this dissertation:

- a. The design produced needs to be portable.
- b. The design produced needs to be cost effective.
- c. The design produced needs to be expandable.
- d. The design produced needs to conceptually allow the SDR ground station to operate in the 70-cm band.

Table 5.1 is populated with the items identified as physical embodiments of the elements found in Conceptual Design 4 in Fig 4.4. The Table lists the items, supplier, country of origin and the cost. The rationale for these component selections is presented in the following subsections.

Table 5.1 COTS components identified for the embodiment design of the SDR ground station.

Item	Type	Supplier	Country	Date of Quote	Cost (R)
Antenna & Accessories	70cm X-Quad	WiMo Antennen & Elektronik GmbH	Germany	2018/04/20	2055.79
	Phasing Harness	WiMo Antennen & Elektronik GmbH	Germany	2018/04/20	929.88
Rotator & Accessories	Yaesu G5500 (Rotator and Controller)	Universal Radio	USA	2018/04/20	9016.84
	6m #20 AWG wire	UCT	South Africa	2018/04/20	0
Microcontroller & Accessories	Arduino Mega 2560 (Assembled)	Netram	South Africa	2018/04/20	297.24
	#196 Proto Screw Shield (Daughter board)	Amazon	USA	2018/04/20	264.39
	LCD Screen and circuitry	UCT			0
	5m Active USB Cable	Takealot	South Africa	2018/04/20	70
SDR & Accessories	RTL-SDR RTL-SDR Blog R820T2 RTL2832U	Amazon	USA	2018/04/20	324.03
Computer	Windows 7 Operating System	UCT			0
TOTAL					12958.17

The antenna's specifications are shown in Table 5.2. Figure 5.1 shows an image of the antenna, together with its phasing harness. The user manual is presented in Appendix 2.

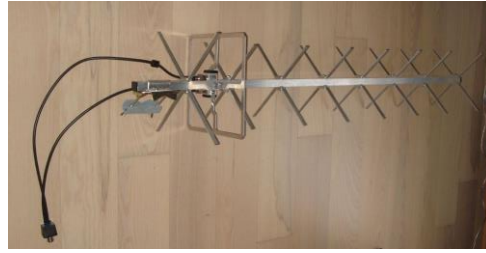


Figure 5. 1 The X-Quad antenna with phasing harness.

Table 5. 2 Quad-X antenna properties. [87]

Aspect	Value
Elements per polarisation plane	18
Gain	12.8 dBD
3dB angle horizontal (E)	36 °
Vertical (H)	36 °
Front/Back ratio	21 dB
Maximum power ratio	1000 Watt
Stacking distance	1.1 m
Length	1270 mm
Height	220 mm
Weight	1.6 Kg
Connector	2 x N jacks

In discussions with 1KUNS-PF ground station crew members, it was advised that even though they would encourage ground stations to use an antenna with gain 16dBi or more, this antenna's gain was suitable to make contact with 1KUNS-PF because of its advantageous cross polarization characteristic. Cross polarization is a necessary antenna related attribute because small satellites generally have erratic and unpredictable attitudes. The X-Quad antenna also had the added benefit over other antennas because it could be set up to be Right Hand Circularly Polarized (RHCP) and Left Hand Circularly Polarized (LHCP) with the help of its phasing harness. Another factor that governed the selection of the X-Quad was the fact that it is compact, with linear dimensions of 0.22 x 1.27 m, and it only has a mass of 1.6 kg, making it very easily portable.

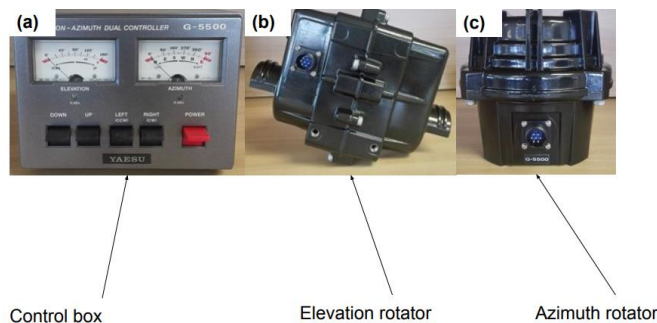


Figure 5. 2 A (a) rotator control box, (b) elevation rotator and (c) azimuth rotator.

The Yaesu G5500 rotator, which includes the azimuth and elevation rotators and their control box pictured in Figure 5.2, was chosen because of Yaesu has a major user community in the amateur radio sector. The Yaesu G5500 rotator was advantageous because it could operate in the azimuth and elevation planes. This characteristic is ideal for tracking small satellites because their position changes continually over time. The Yaesu G5500 is a tried and tested piece of equipment in the amateur radio community and it is capable of working with other rotator interfaces in addition to its own. Design 4 specified that the rotator interface needed be constructed from a microcontroller and, after researching how this could be done, it was decided that the best option for this project was to construct the rotator interface using an Arduino Mega 2560 and #196 Proto Screw Shield from the AMSAT-UK rotator interface developed by British amateur radio enthusiast Tom Doyle, as shown in Appendix 3. The code compatible with this design is discussed in software section of this chapter. The Yaesu G5500 specifications are shown in Table 5.3.

Table 5. 3 Yaesu G5500 specifications. [88]

Aspect	Value
Voltage requirement	110 - 120 or 200 – 240 VAC
Motor voltage	24 VAC
Rotation time (60Hz)	Azimuth (360 °): 58 s
	Elevation (180 °): 67 s
Maximum continuous operation time	5 minutes
Rotation torque	Azimuth: 14 kg-m
	Elevation: 6 kg-m
Braking torque	Azimuth: 40 kg-m
	Elevation: 40 kg-m
Vertical Load	200 kg
Pointing accuracy	±4 %
Mass	Rotators: 9 kg
	Control box: 3 kg
Mast Diameter	38 – 63 mm
Boom diameter	32 43 mm

In addition to the above-mentioned reasons, the G5500 had a total mass of 9 kg, which was advantageous because the SDR ground station needed to be portable. The rotator was also rated to operate between 200-240 VAC @ 50 Hz, which lies within the power requirements for this dissertation.

The 6 m, 6-core and #20AWG wire, displayed in Figure 5.3, was chosen to connect the rotator control box to the azimuth and elevation rotators, as specified in the Yaesu G5500 manual shown in Appendix 4. The wire was readily available at UCT and therefore did not contribute to the overall cost, which was advantageous.

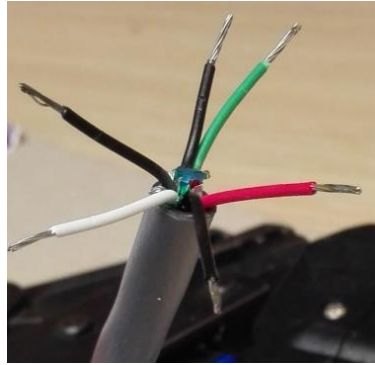


Figure 5. 3 6-core #20 AGW wire.

As mentioned above, the Arduino Mega 2560, whose details are shown in Table 5.4 and image in Figure 5.4, and one of its daughter boards, #196 Proto Screw Shield, whose parts list and assembly manual is shown in Appendix 5, was chosen to form the rotator interface. This, as previously alluded to, was chosen because it is a tried and trusted design from AMSAT-UK. Choosing to use an established design considerably decreased this project's timeline. The Arduino Mega 2560 was well priced and is designed to be expandable, which is directly seen through the collaboration with its daughter board to form a rotator interface. Another reason why this microcontroller was chosen is because there is a large community of Arduino users who consistently provide support and documentation for fellow users of this platform.

Table 5. 4 Arduino Mega 2560 characteristics. [89]

Microcontroller	ATmega2560
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limit)	6-20 V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
LED_BUILTIN	13
Length	101.52 mm
Width	53.3 mm
Weight	37 g

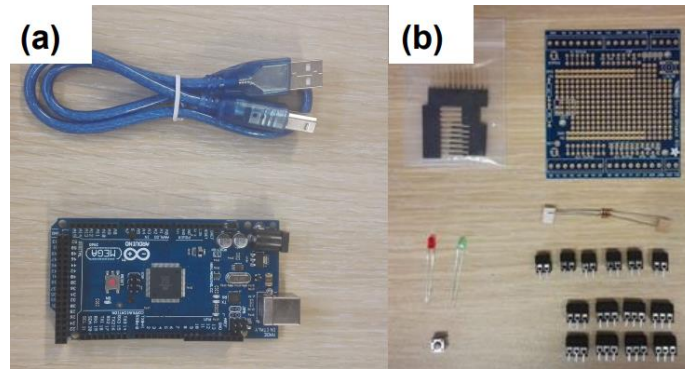


Figure 5. 4 The (a) Arduino Mega 2560 with its USB connector and (b) daughter board.

A 5m active USB cable, shown in Figure 5.5, was also purchased to link the Arduino Mega 2560 to the computer because the USB cable provided with the Arduino was only 15 cm in length. USB active cables have similar attenuation values so this one was chosen based on its price and availability.



Figure 5. 5 The active USB cable.

An LCD screen was acquired from UCT to support the rotator interface's design, shown in Appendix 3. When connected to the rotator interface it is able to display azimuth and elevation values related to a satellite being tracked. The LCD screen is shown in Figure 5.6. The assembly of the LCD screen and its circuitry is shown and described in depth in the assembly part of the chapter.



Figure 5. 6 The LCD screen used to display azimuth and elevation values. [90]

A multitude of SDR's satisfied the ground station's requirement of being able to receive signals in the 70-cm band because many of them on the market are based on similar designs. The RTL-SDR, based on DVB-T TV tuners with RTL2832U chipsets, was chosen because of the support it has received from the amateur radio community, documentation and supplier guarantee.

Table 5. 5 SDR comparison table. [91]

SDR	Tune Low (MHZ)	Tune Max (MHZ)	RX Bandwidth	ADC Resolution (Bits)	Transmit (YES/NO)	Price (\$USD)
RTL-SDR (R820T)	24	1766	3.2	8	NO	20
Funcube Pro+	0.16 410	260 2050	0.192	16	NO	200
Airspy	24	1800	10	12	NO	199
SDRPlay	0.1	2000	8	12	NO	149
HackRF	30	6000	20	8	YES	299
BladeRF	300	3800	40	12	YES	400
USRP 1	DC	6000	64	12	YES	700

Table 5.5 shows the comparison of other SDRs and the RTL-SDR. The RTL-SDR is most advantageous amongst the other listed SDRs because of its attractive selling price. The other characteristics listed in the table are dependent of the SDR's purpose. For the purpose of this ground station, having a very low or extremely high tuning level was not of great concern. The SDR just had to be able to work within the 430-440 MHz range. The RTL-SDR's receiving bandwidth as compared to the other SDRs was the second lowest and it had one of the lowest Analog-to-Digital Converter resolutions, 8 Bits. These attributes could have been improved however for the purpose of this ground station they were acceptable given its extremely low price. The RTL-SDRs parts are shown in Figure 5.7.

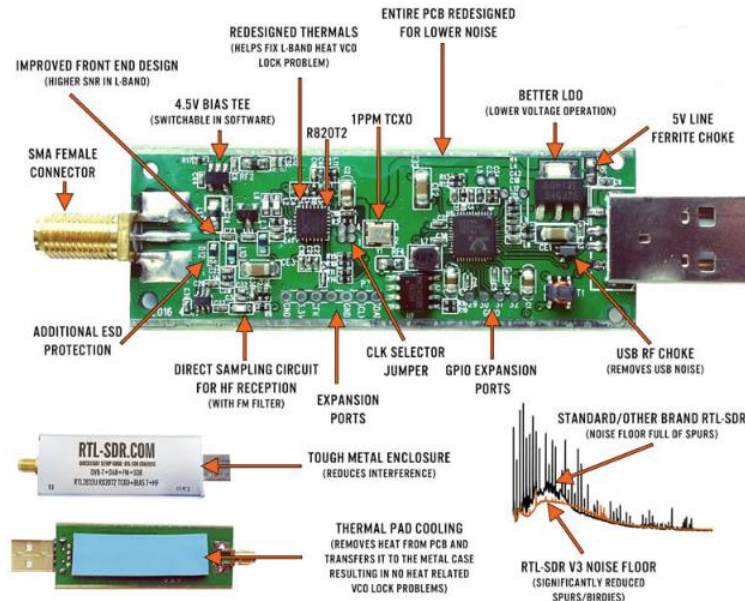


Figure 5. 7 A diagram showing what the RTL-SDR is composed of. [92]

Lastly, a desktop computer running Windows 7 was assigned to this SDR ground station and acquired freely from UCT, the main reason why it was chosen. The computer specifications are shown below in Figure 5.8.

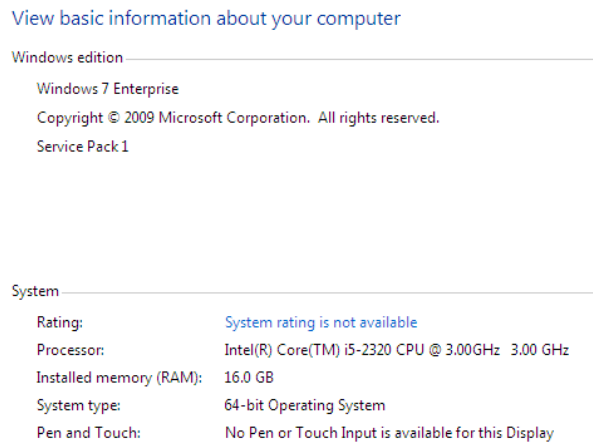


Figure 5. 8 A screen shot of the properties of the desktop used to run the SDR ground station.

The items discussed above were assessed against the criteria in the Mission Statements and repeated at the start of this Chapter. Table 5.6 shows that all the chosen items met the assessment criteria and provides the rationale for our selections.

Table 5. 6 Assessment against criteria in the Mission Statement.

Criteria	YES/NO	Reasoning
Cost effective	YES	Cost-intensive elements were substituted by cost-effective items. The total cost was estimated to be R 12888, below the total budget of R 20,000, leaving a total of R 7112 for the remaining ground station items.
Portable	YES	The system requires a power source. If the system is used in a well electrified area, then mains power can be used. Alternatively, if it is used in an un-electrified area, then a portable power source can be used.
Expandable	YES	The system is not bulky, thereby leaving room for expansion. The items chosen are easily expandable. Therefore, there is room for growth and future customization.
Operate on small LEO satellite in the 70cm band	YES	A directional 70-cm band and cross-polarized antenna was chosen for the ground station so the antenna should be able to make contact with small satellite in LEO operating within the 70cm band. A rotator that has both azimuth and elevation degrees of freedom was chosen to help the antenna track small satellites in LEO.

Figure 5.9 shows the conceptual design 4 in Figure 4.4, but extended to include the details of the COTS components selected for the embodiment of Conceptual Design into a detailed design for the SDR ground station.

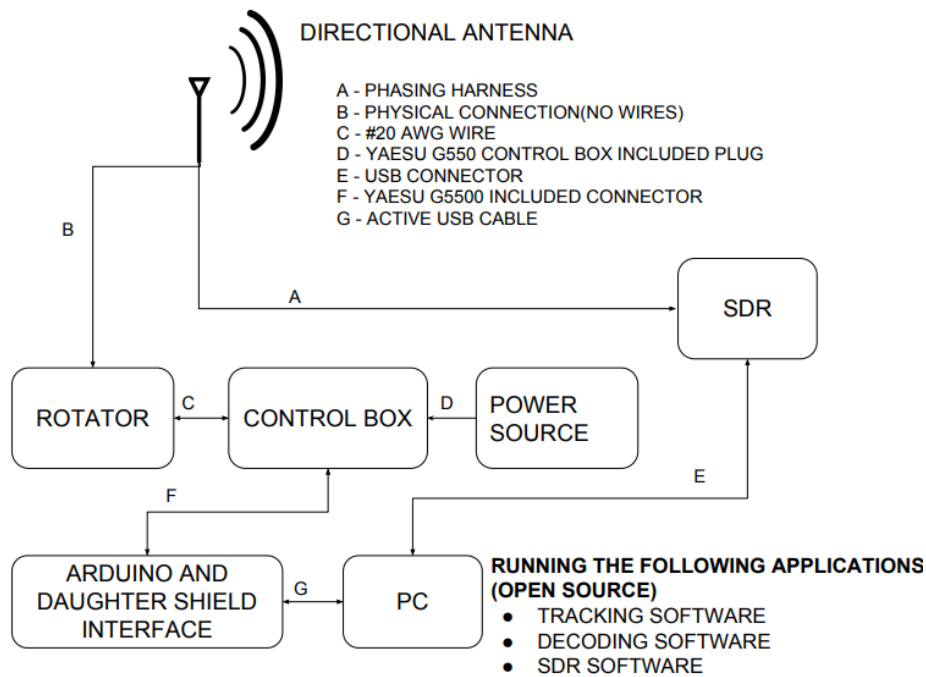


Figure 5. 9 An updated version of the ground station based on the additions made in Table 5.1.

5.2 Detailed Structural Design

Now that we have identified the COTS components to be used in the embodiment of the conceptual design, we can perform the detailed structural design of the ground station. This involves an analysis of the mechanical loads imposed by the weight of the

various elements in the design, as well as wind loads to be experienced in operation. These requirements and constraints are expressed in Table 5.7

Table 5.7 Requirements and constraints for the structural design of the ground station.

Aspect	Explanation
Wind	The ground station needs to be able to withstand a maximum wind speed of $5 \text{ m} \cdot \text{s}^{-1}$ at its centre of mass.
Height	The ground station needs to be under 2 m tall when its antenna is positioned directly in the azimuth plane.
Weight	The mass of the entire ground station must be equal to or less than 50 kg to be considered portable.

Keeping the assessment criteria in mind the structural design, shown in Figure 5.10, depicts how the ground station was envisioned to look like together with the items identified in Table 5.1.

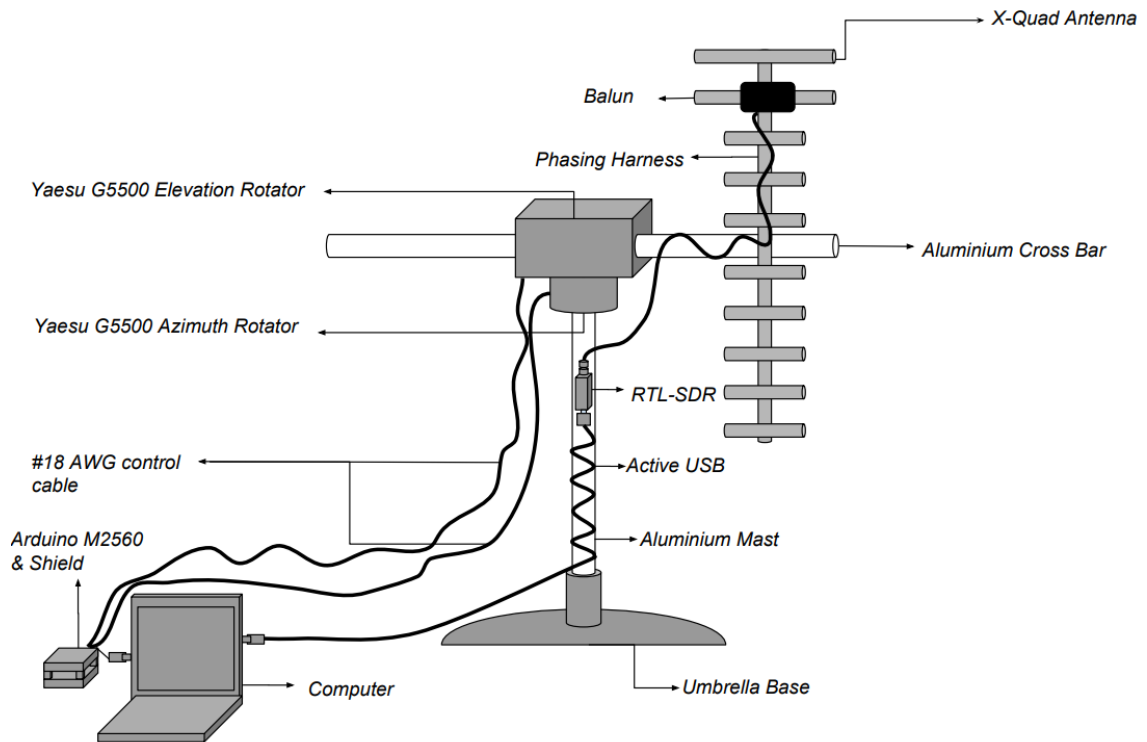


Figure 5.10 A depiction of the structural elements of the ground station.

Table 5.8 lists the structural elements with their purpose with respect to the other ground station elements.

Table 5.8 The ground station's structural and elements.

Item	Quantity	Purpose
Aluminium Cross Bar	1	Supports the antenna and is inserted into the Yaesu G5500 elevation rotator as per the Yaesu G5500 instructions found in Appendix 4.
Aluminium Mast	1	Supports the antenna, cross bar and Yaesu G5500 elevation and azimuth rotators as per the Yaesu G5500 instructions found in Appendix 4.
Concrete Outdoors Umbrella Base	1	Supports the mast, Yaesu G5500 rotators, the cross bar and antenna.

The concrete umbrella base was chosen because these are widely available from local suppliers in South Africa; they come in a wide range of shapes and sizes; they are cost effective and portable.

The aluminium mast and boom were chosen because they were light weight; widely available; cost effective; easy to manipulate and they do not rust.

In order to determine the required strength of the mast and cross-bar as depicted in Figure 5.10, we next performed an analysis of the loads expected to be experienced by these structural members.

The process to quantify the structural elements began by addressing the first criteria in Table 5.7, wind. In order to figure out if the ground station could withstand a wind speed of $5 \text{ m} \cdot \text{s}^{-1}$, the force of the wind relating to $5 \text{ m} \cdot \text{s}^{-1}$ and the sum of moments about the right-most edge of the umbrella base needed to be calculated. The following representative values, selected within the boundaries of this project's objectives, requirements and constraints, were chosen to assist in the calculations:

- Mast – 1.3m in length with a 38 mm diameter tube (Negligible weight)
- Crossbar- 1m in length with a 38 mm diameter tube (Negligible weight)
- Umbrella base – 30 kg

To calculate the force of the wind Equation 5.1, shown below, was used.

$$F_w = \frac{1}{2} \rho v^2 A \quad \text{Equation 5.1}$$

where,

F_w = The force of wind on a surface area (N)

ρ = Air density $\left(\frac{\text{kg}}{\text{m}^3}\right)$

v = The speed of wind $\left(\frac{\text{m}}{\text{s}}\right)$

A = The total surface area on which the air acts upon $\left(\frac{\text{m}^2}{\text{s}}\right)$

At this point ν was known however, ρ and A were not. Finding the value ρ required Equation 5.2 to be used.

$$\rho = \frac{P}{RT} = \frac{P_d}{R_d \times T_a} + \frac{P_v}{R_v + T_s} \quad \text{Equation 5.2}$$

where,

ρ = Air density ($\frac{kg}{m^3}$)

P = Pressure (PA)

R = Specific gas constant ($\frac{J}{kg \cdot K}$)

T = Absolute temperature (K)

T_a = Absolute air temperature (K)

T_s = Absolute sea temperature (K)

P_d = Pressure of dry air (PA)

R_d = Gas constant for dry air ($\frac{J}{kg \cdot K}$)

P_v = Pressure of water vapour (PA)

R_v = Gas constant for water vapour ($\frac{J}{kg \cdot K}$)

In order to populate Equation 5.2, the following figures in Table 5.9 were used

Table 5.9 Values used to populate Equation 5.2. [93]–[95]

Variable	Value	Reason
P_d	101694	The average value of the air pressure in Cape Town.
P_v	2131	The average water vapour pressure in Cape Town.
T_a	290.15	The average Cape Town air temperature in 2018, 17°C, represented in Kelvin.
T_s	291.65	The average Cape Town sea temperature in 2018, 18.5°C, represented in Kelvin.
R_v	461.50	The gas constant for water vapour.
R_d	287.05	The constant given to dry air.

Using the above values, ρ , came to $1.237 \left(\frac{kg}{m^3}\right)$.

Next, to find the value of A in Equation 5.1, approximations were made for the surface areas of the front, back and side of the ground station. In order to simplify the surface area calculations for each item in each view was reduced to rectangles, as shown in Figures 5.11 and 5.12.

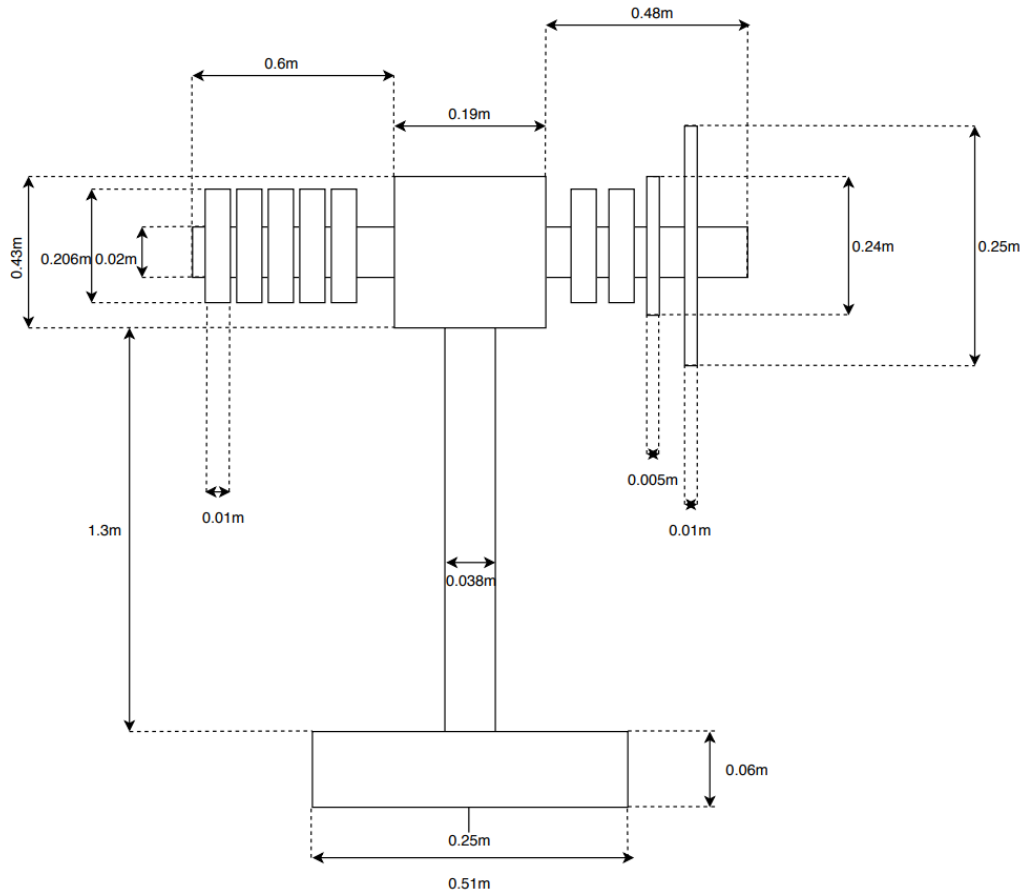


Figure 5.11 The side view of the SDR ground station approximated to rectangular shapes.

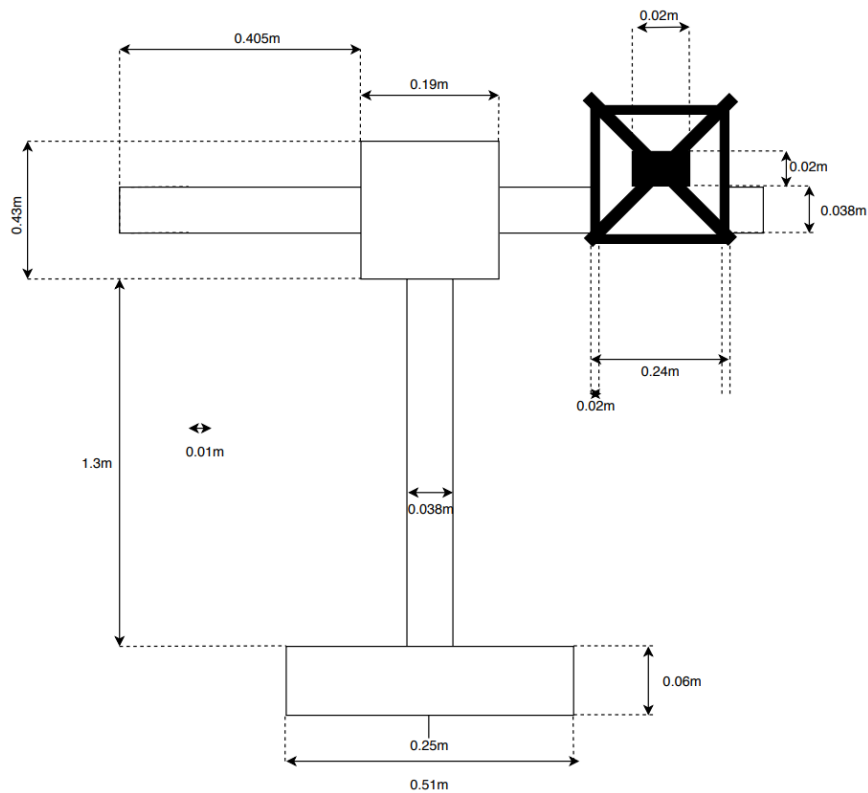


Figure 5.12 The front and back view of the SDR ground station approximated to rectangular shapes.

The corresponding surface area values for the side, front and back views were determined to be:

- Side view surface area - 0.201 m^2
- Front and back view surface area - 0.137 m^2

F_w was then calculated for all three surface area values using Equation 5.1. Their values were as follows:

- Wind force of the side view $F_{ws} = 2.506 \text{ N}$
- Wind force on the front and back views $F_{wf}, F_{wb} = 2.118 \text{ N}$

With the respective values of F_w known, to determine whether the various forces of wind acting on their respective views (Figure 5.13) would destabilize the ground station, Equations 5.3-5.8 were used to calculate the sum of moments about the right-most edge point, E_{point} , on the umbrella base. The distance from the centre point, C_p , to the E_{point} is given by, R_{centre} . A positive sum of moments indicates that the F_w acting on it will not destabilize it; a negative value indicates that it will be destabilized it and a value of zero signalizes a metastable critical region between both extremes.

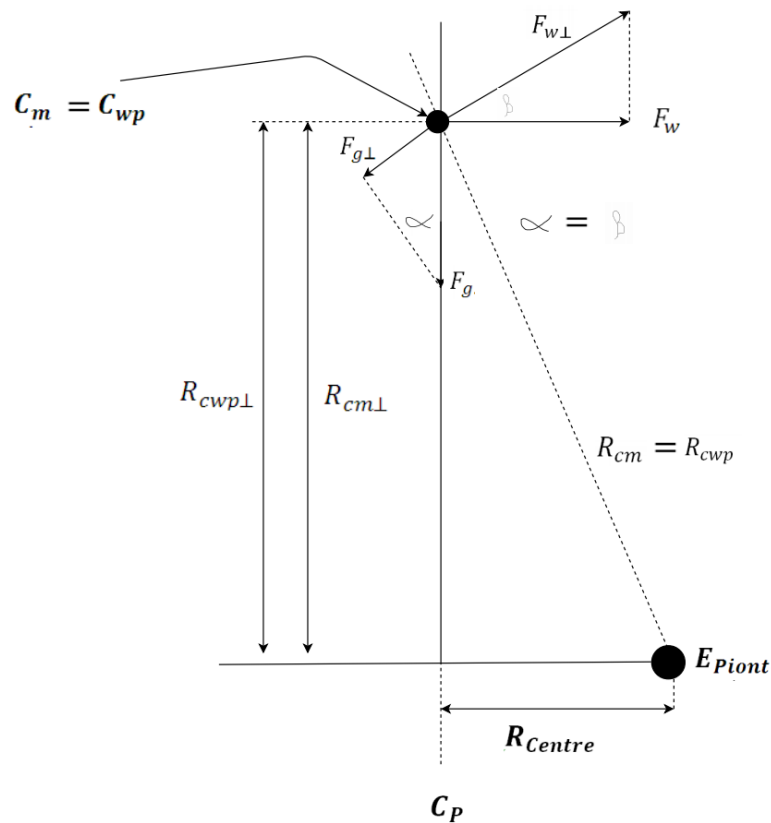


Figure 5. 13 The forces acting on the ground station with wind acting on its centre of mass.

According to the wind constraint outlined in Chapter 3, the force of wind needs to be tested at the centre of the SDR ground station's mass. Therefore, as shown in Figure 5.13 the centre of mass of the SDR ground station C_m and the centre of wind mass C_{wp} are equal. To work out the value of C_m and subsequently the value of C_{wp} the centre of mass equation, Equation 5.3, was used. C_m and subsequently C_{wp} was calculated to be 0.339 m

$$C_{wp} = C_m \frac{m_1x_1 + m_2x_2 + \dots + m_zx_z}{m_1 + m_2 + \dots + m_z}, z > 0 \quad \text{Equation 5.3}$$

where,

C_{wp} = Centre of wind mass point

C_m = Centre of mass of the SDR ground station

m_z = Mass of the body

x_z = Distance from objects to C_p

Once the centre of masses was found, the moments about the E_{piont} needed to be calculated using Equation 5.4.

$$\sum M = F_{g\perp}R_{cm} - F_{w\perp}R_{cwp} \quad \text{Equation 5.4}$$

where,

$\sum M$ = Sum of moments

$F_{w\perp}$ = The perpendicular force of F_w

$F_{g\perp}$ = The perpendicular force of F_g

R_{cwp} = The diagonal line's distance from C_{wp} to E_{piont}

R_{cm} = The diagonal line's distance from C_{cm} to E_{piont}

The sum of moments about E_p , $F_{g\perp}$ and $F_{w\perp}$ had to be found using Equations 5.5 and 5.6.

$$F_{g\perp} = F_g \sin \alpha = mg \sin \alpha \quad \text{Equation 5.5}$$

where,

$F_{g\perp}$ = The perpendicular force of the ground station

α = The resultant angle between F_g and $F_{g\perp}$

F_g = The perpendicular force of the ground station

m = The mass of the SDR ground station

g = Gravitational acceleration on Earth, $9.8 \text{ m} \cdot \text{s}^{-2}$

$$F_{w\perp} = F_w \cos \beta \quad \text{Equation 5.6}$$

where,

$F_{w\perp}$ = The perpendicular force of the wind

β = The resultant angle between F_w and $F_{w\perp}$

F_w = The perpendicular force of the wind pressure

However, the values of α and β shown in Figure 5.13 and Equation 5.7 had to be found first. Their values were calculated to be 36.41° since the perpendicular distance from the centre of mass C_m to C_p , $R_{cm\perp}$, equated to the perpendicular distance from the to C_{wp} to C_p , $R_{cwp\perp}$. Consequently, Equation 5.6 was applied two times by substituting $F_{wf} = F_{wb}$ and F_{ws} each time for F_w to produce $F_{wf\perp} = F_{wb\perp}$ and $F_{ws\perp}$. $F_{wf\perp} = F_{wb\perp}$ was calculated to be 2118 N and $F_{ws\perp}$ was calculated to be 2.506 N. Lastly $F_{g\perp}$ was calculated to be 236.170 N.

$$\alpha = \beta = \tan^{-1} \frac{R_{centre}}{R_{cm\perp}} = \tan^{-1} \frac{R_{centre}}{R_{cwp\perp}}, \quad \text{Equation 5.7}$$

since $R_{cm\perp} = R_{cwp\perp}$

where,

α = The resultant angle between F_g and $F_{g\perp}$

β = The resultant angle between F_w and $F_{w\perp}$

$R_{cm\perp}$ = The perpendicular distance from C_m to C_p

$R_{cwp\perp}$ = The perpendicular distance from C_{cwp} to C_p

Then R_{cwp} and R_{cm} was needed to sum the moments about the right-most edge of the umbrella base. They were found using Equation 5.8.

$$R_{cwp} = \sqrt{R_{centre}^2 + R_{cwp\perp}^2} = \sqrt{R_{centre}^2 + R_{cm\perp}^2} = R_{cm} ,$$

since $R_{cm\perp} = R_{cwp\perp}$

Equation 5.8

where,

R_{cwp} = The diagonal line's distance from C_{wp} to E_{piont}

R_{cm} = The diagonal line's distance from C_{cm} to E_{piont}

R_{centre} = Distance from C_p to E_{point}

$R_{cm\perp}$ = The perpendicular distance from C_m to C_p

$R_{cwp\perp}$ = The perpendicular distance from C_{cwp} to C_p

Having solved for all the variables in Equation 5.4, $\sum M_s$, and $\sum M_f = \sum M_b$, were calculated to be 98.129 Nm and 99.413 Nm, respectively. The sum of all moments on each view were calculated to be positive. Therefore, it was concluded that a wind speed of $5 \text{ m} \cdot \text{s}^{-1}$ acting on the SDR ground station's centre of mass would not destabilize it if the:

- Mast was 1.3 m in length with a 38 mm diameter tube (Negligible weight)
- Crossbar was 1 m in length with a 38 mm diameter tube (Negligible weight)
- Umbrella base was 30 kg

Table 5.10 lists the results of our structural analysis.

Table 5. 10 Assessment of structural properties against requirements and constraints.

Aspect	Passed	Explanation
Wind	Yes	A wind speed of $5 \text{ m} \cdot \text{s}^{-1}$ acting at the SDR ground station's centre of mass will not topple it over.
Height	Yes	The total height of SDR ground station when the antenna is levelled horizontally to the ground is under 2 m
Weight	Yes	The structural elements have a mass of 40.6 kg, which is under the 50 kg mass limitation.

5.3 Parts Acquisition for Antenna and Rotator Support Structure

Having sized the various structural elements, we were able to procure them. Since the antenna, rotator, microcontroller, SDR, and their various accessories cost just under R 13,000, we had to procure the structural elements for under R 7000 to stay within the

R 20,000 budget for the ground station. Table 5.11 presents acquisition information and costs for these various items.

Table 5. 11 Parts acquisition for antenna and rotator support structure.

Item	Name	Range	Supplier	Country	Cost (R)	Date of Quote
Umbrella base	Concrete Umbrella base	30-40 kg	Takealot	South Africa	574	2018/09/05
Mast	Aluminium mast	1.3-2 m	Uniterm Direct	South Africa	155.25	2018/09/05
Cross bar	Aluminium mast	1.3-2 m	Uniterm Direct	South Africa	155.25	2018/09/05
Total					884.50	

The total cost of the support structure came to R 884.50, which kept us well within the R 20000 budget. This left us some margin for software and other costs.

5.4 Software

The different types of software used when operating the ground station are described in this section. This section does not cover information pertaining to the downloading and installing of software, however, a collection of sources with instructions on where to download software and how to install it are provided in Appendix 6. This section provides descriptions about the software applications; why they were used for the SDR ground station and it also provides screenshots of important features used within this dissertation. The system used to install the different software packages ran Microsoft Windows 7 and evidently all the software applications were compatible with Microsoft Windows 7 and not dependent on virtual-machine-run operating systems.

5.4.1 SDR#

SDR#, pronounced SDR sharp, was used to visualise radio frequencies associated with the SDR ground station. It allows users to visually toggle through different radio frequencies; choose demodulation modes and record signals, all in near real time. [96]

This software was deemed necessary to use in this project because of its features, documentation, reputation and user-friendly interface. Figure 5.14 displays the main screen seen by a SDR# user. The notable options used in this project are described below.

- Waterfall display: Displays frequency over time.
- Frequency Input: Allows the user to key in their desired frequency
- FFT Graphs controls.
 - Zoom: Allows the user to zoom into a specific signal visually.
 - Range: Allows the user to investigate a particular range.
- Device selection: Allows the user to choose their SDR type. In this case it was RTL-SDR.

- Demodulation: Allows the user to choose different frequency modulation modes.
- Recording: Allows the user to record frequency audio for post processing.
- RF FF: The section where the frequencies are seen.

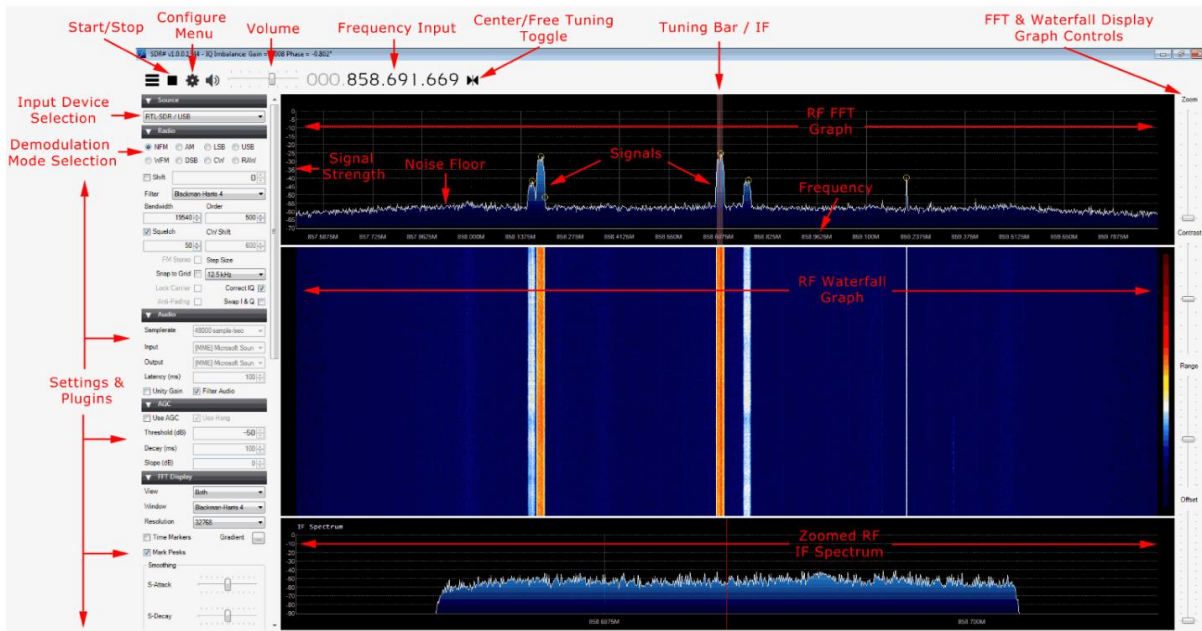


Figure 5. 14 A screen shot of the main screen in SDR#. [96]

5.4.2 SatPC32

To visually track small satellites in LEO, SatPC32 was downloaded and installed. SatPC32 allows a user to visualise one or more satellite footprints, on mapped backgrounds, from a given or created list of satellites. In addition to allowing the user to visually track satellites, SatPC32, when interfaced with an antenna rotator, can automate and influence the rotator's motion based on its available tracking information. Figure 5.15 illustrates the main user interface.

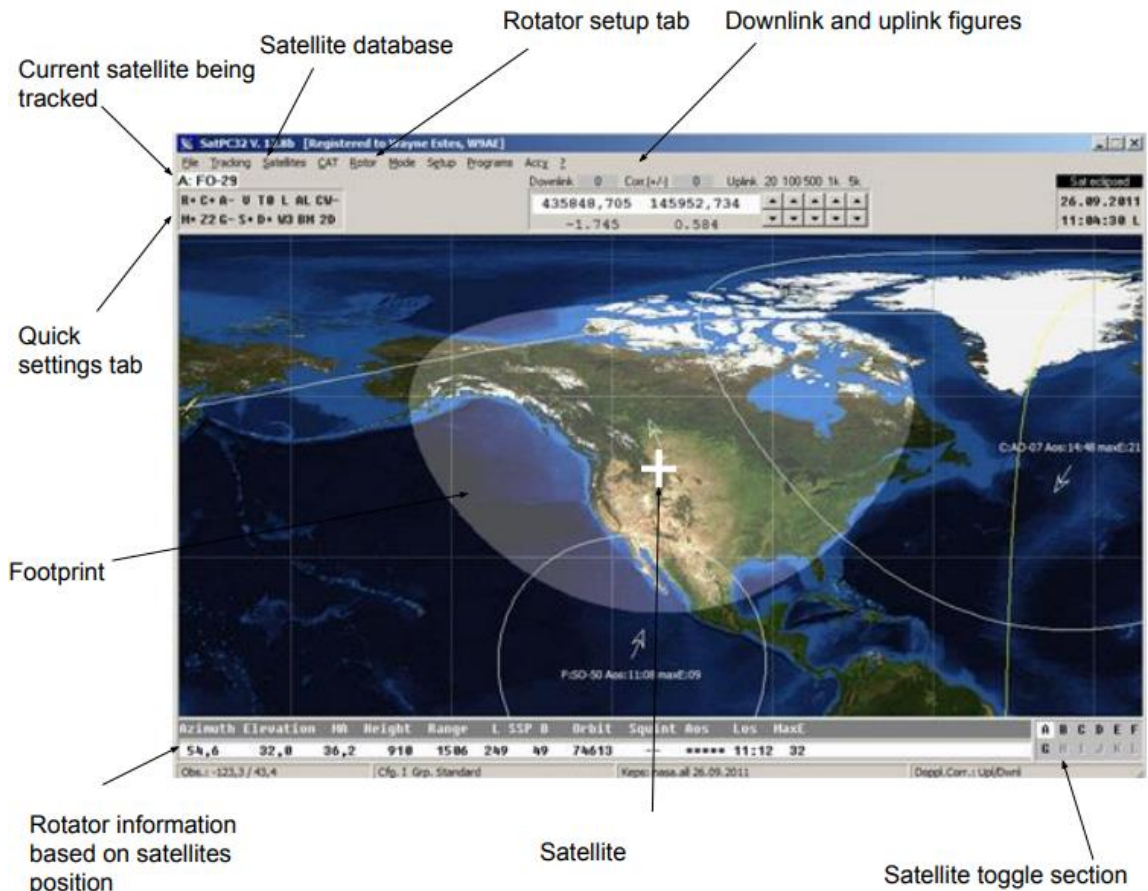


Figure 5. 15 A screen shot of SatPC32 and its notable features.

5.4.3 Arduino and Shield Rotator Software

The Arduino and shield rotator interface is made up of a hardware and software components. This section focuses on the software aspects. Open source software was used to calibrate an Arduino and shield to act as an antenna rotator. The software, titled SimpleSat Rotator Control Program, was originally written by amateur radio enthusiast Tom Doyle in January 2012. The code emulates the Yaesu rotator interface by using instructions and protocols specific to its design. The code primarily interacts with SatPC32 to acquire tracking information in five-second intervals. Once it acquires tracking information, it is able to send messages to the rotator controller in order for it to update the rotator's azimuth and elevation positions. In addition to this the software is able to visually output the rotator's elevation and azimuth positions on an LCD screen for verification purposes. The code is available in Appendix 7

5.4.4 N2YO.COM

N2YO.COM is a website that provides users with near real-time tracking information for a multitude of satellites. This site was used to find information pertaining to what amateur satellites were in range of the SDR ground station. N2YO.COM uses the geographical coordinates of the computer a user is using to access the website to provide the user with specific information about which satellites are above their

horizon. The main attributes that were used on this site are highlighted in Figure 5.16 and explained below.

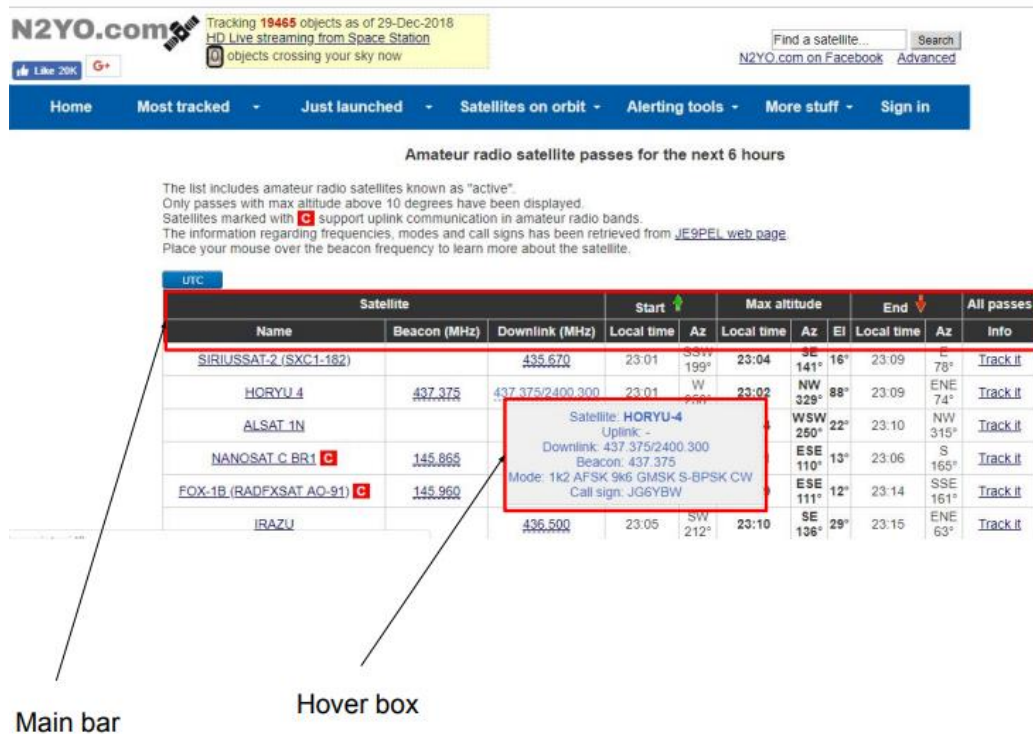


Figure 5. 16 A screen shot from N2YO.com.

- Main bar
 - Name: The names of the satellites were recorded from here so that they could be used in accompanying SDR ground station software applications.
 - Downlink (MHz): Satellite's downlinking frequency was used recorded so the SDR ground station knew which signal to lock on to.
 - Start
 - Local Time: An approximated start time when a satellite's foot print first enters the ground stations vicinity.
 - Az: The azimuth value at the start local time (Used to check if tracking system was working correctly).
 - Max altitude
 - Local time: The time associated with a satellite's maximum altitude above the user's horizon.
 - Az: The azimuth value related to the maximum altitude position (Used to check if tracking system was working correctly).
 - El: The elevation value related to the maximum altitude position (Used to check if tracking system was working correctly).
 - End
 - Local Time: An approximated end time when a satellite's foot print leaves the ground station's vicinity.
 - Az: The azimuth value at the end local time (Used to check if tracking system was working correctly)
- Hover box: Appears when a user hovers over beacon or downlinking frequencies. The modes and call signs were recorded from here.

5.4.5 HS-Sound modem

Sound modem, written by Thomas Sailer, is a software-based AGW PE, an interface between packet radio software and related hardware, enabled application that allows a sound card located in a PC to be utilized as a traditional packet radio modem. It achieves this by executing tasks on the PC's main CPU. [97], [98] The software has TCP and IP interfaces that help it link to supporting programs such as AGW Online Kiss described in 5.4.6. It also supports the AX.25 protocol, a data link layer protocol, used by amateur radio operators and in many satellite packets.[99]

Sound modem analyses and processes audio waves emanating from a computer. In this project Sound modem got its audio frequency input from SDR#. The varying audio signals produced by a satellite and heard through SDR# were then transferred from SDR# to Sound modem where they could be decoded into packets. To transfer the information from SDR# to Sound modem, a complementary software package known as Virtual Audio Cable (VAC), was used. VAC in this thesis acted as the sound bridge between both programs.

Figure 5.17 depicts important features in the main Sound modem interface.

- Waterfall – Time lapse of the signal in real time.
- Information screen – shows incoming data.
- Demodulation mode – signal demodulating mode.

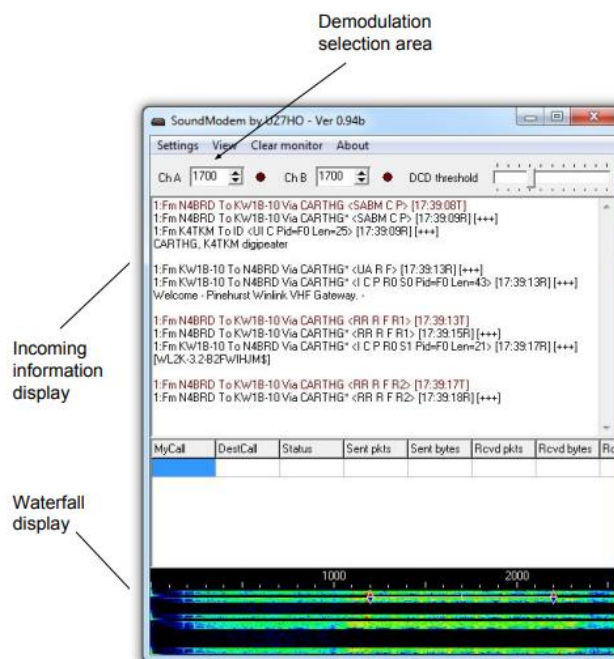


Figure 5. 17 The important aspects on Sound Modem's main user interface. [100]

5.4.6 AGW Online Kiss and Kiss-Dump

AGW Online Kiss is an application that creates KISS, "Keep It Simple Stupid", files from AX.25 telemetry sent from satellites. Many satellites use the KISS format in their packets, however when it is transmitted in this format an AGWE PE based sound modem can't process and decode it. For this purpose, AGW Online KISS is used to decode such packets. This is done by creating KISS files housing hex dump information from the AGW PE enabled sound modem. The information is transferred

from the AGW PE sound modem through a TCP port to AGW Online KISS. Once a KISS file is created, a program called KISS-DUMP can be used to display its information for a user to analyse. The KISS format is useful because many amateur satellites have KISS compatible decoders that can then be used to decode the information stored in the KISS files. [101], [102]

Figure 5.18 and Figure 5.19 highlight the main interfaces of AGW Online KISS and KISS-Dump.

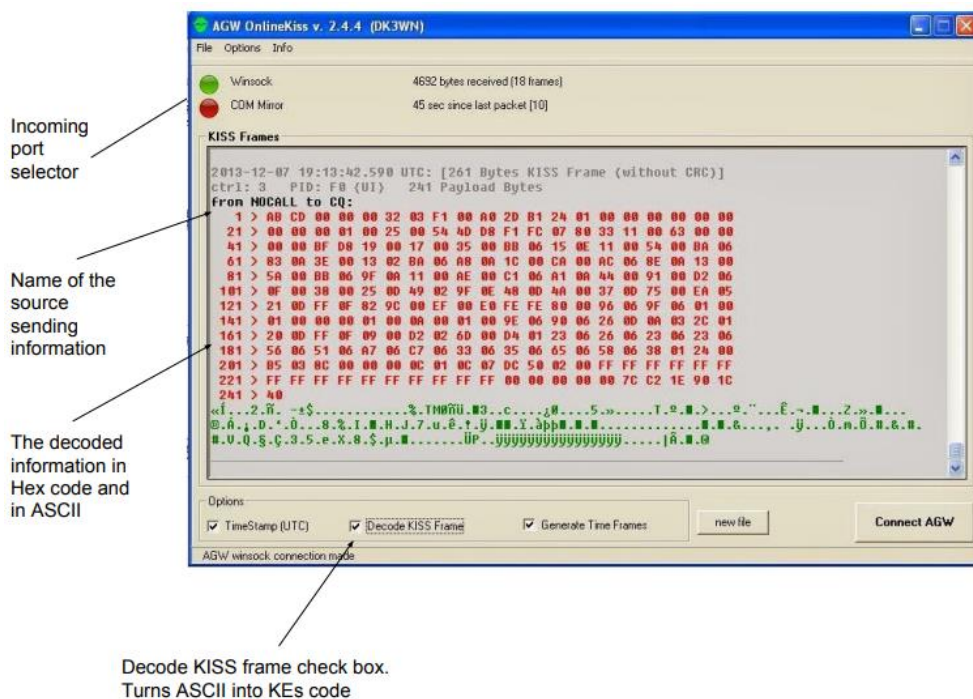


Figure 5. 18 AGW Online KISS main screen features. [103]

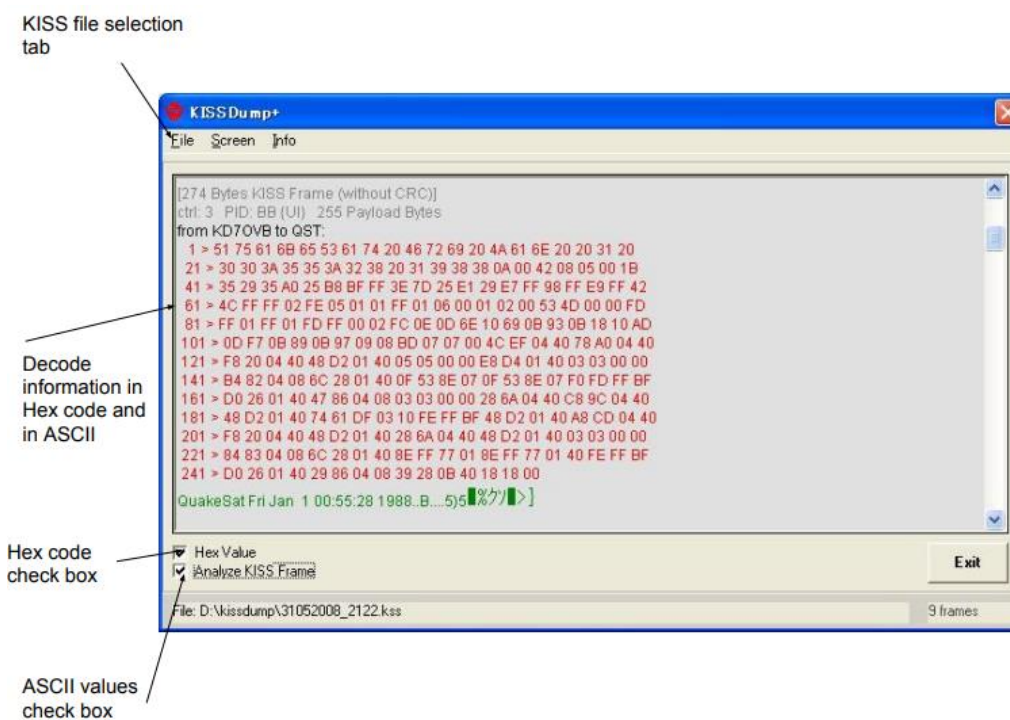


Figure 5. 19 Screen shot of the main features on KISSDump+. [104]

5.4.7 Decoders

As mentioned in 5.4.6, KISS compatible decoders are readily available on the internet. The main source and collection can be found on a website called, “DK3WN SatBlog”. There are a multitude of satellite-specific decoders available and currently being built on this website. Space does not permit us to describe them all here. In this thesis a decoder was only downloaded and installed once packets from a particular satellite were received.

5.5 Assembly, Integration and Testing

This section entails the assembly of the individual SDR ground station items in the SpaceLab lab; the integration of all those items to form the SDR ground station and the testing of the individual subsystems and full system.

5.5.1 Base, Mast and Crossbar

The aluminium mast and crossbar poles that were purchased each had a length of 2m as shown in Figure 5.20. They needed to be cut to 1.3 m and 1 m lengths, respectively. After being cut, the ends of the poles were rough and sharp. From Figure 5.10 it can be seen that only the crossbar’s ends were exposed so they were covered with masking tape for safety purposes. In addition to this, the mast pole had to be drilled, through both walls, with a 9 mm hole, 50mm from one end after it was cut to size as per Yaesu G5500 instructions found in Appendix 4. The hole had to be drilled so that the mast could be connected to the rotators also explained in Appendix 4.

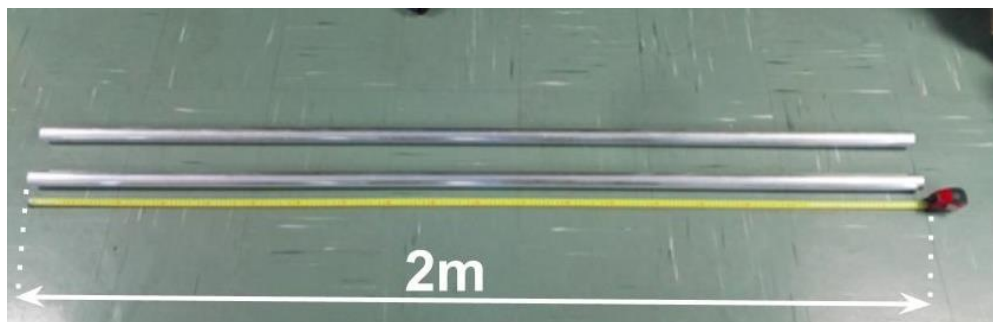


Figure 5. 20 The two mast and cross bar poles before being processed.

The processes performed on the mast and cross bar poles to get them into their desired forms are shown in Figure 5.21 and Figure 5.22, respectively. After the pole processing was conducted, the mast was inserted into the umbrella base with the side with the drilled-out-hole the top end of the pipe. Figure 5.23 shows what the ground station at this stage looked like.

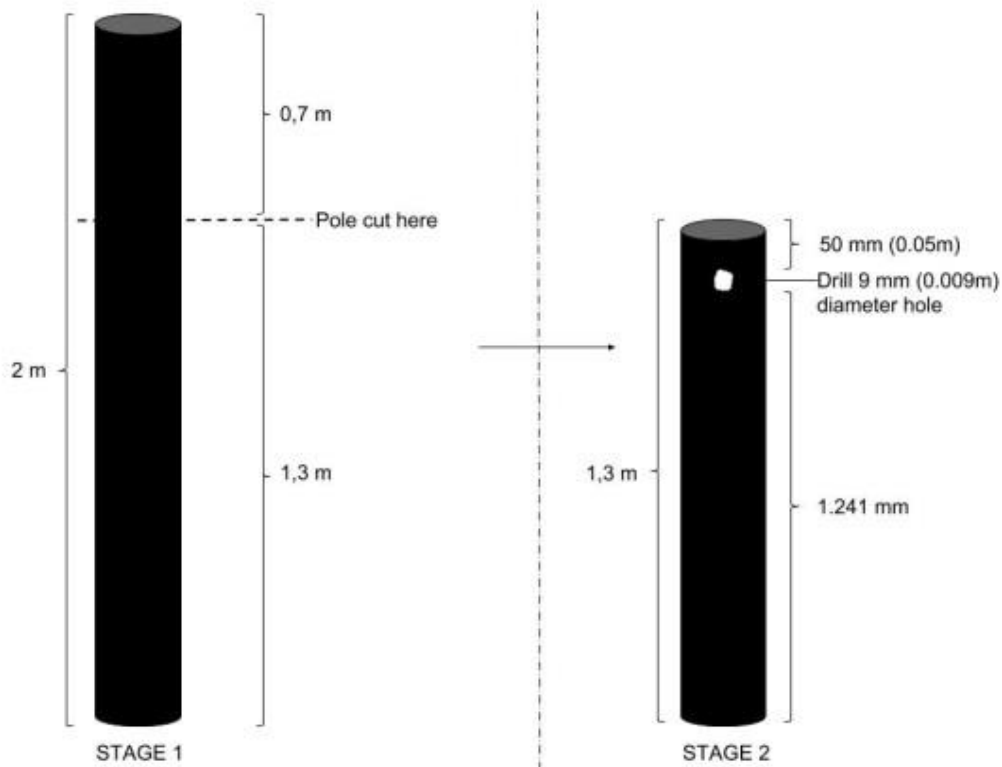


Figure 5. 21 The mast before and after it was cut and drilled.

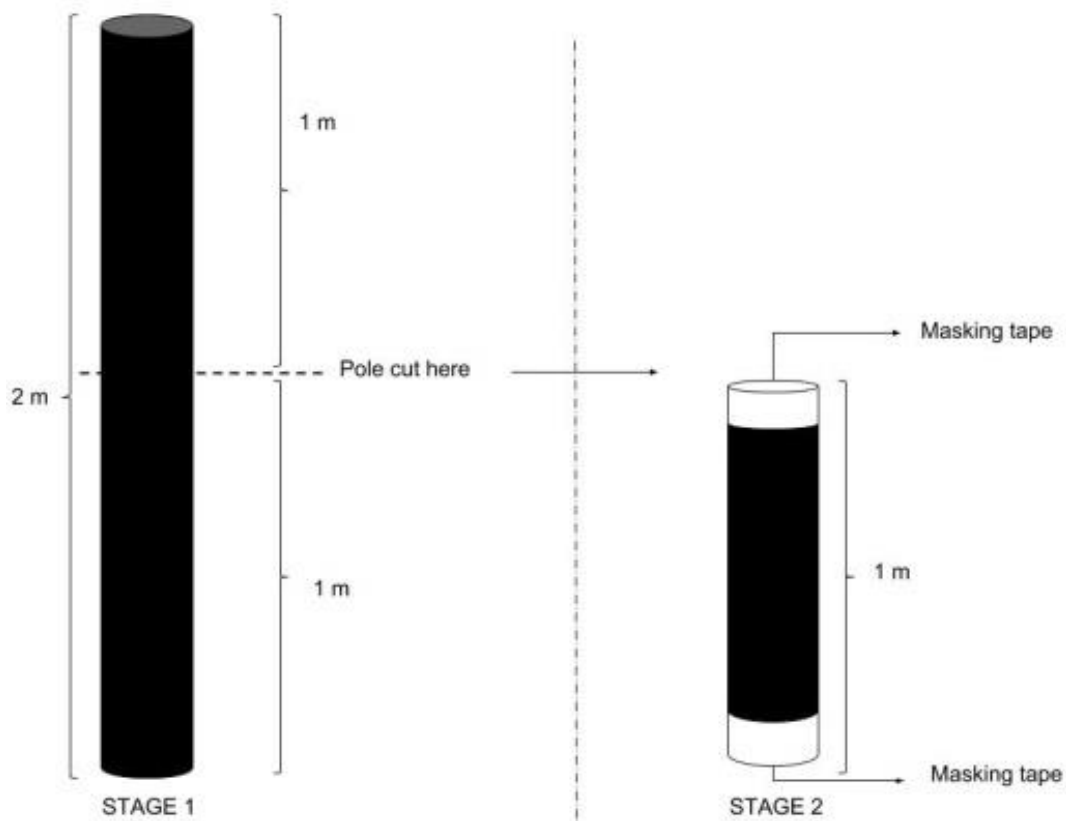


Figure 5. 22 The crossbar before and after it was cut and finished off.



Figure 5. 23 The ground station support mast in its base.

5.5.2 Azimuth, Elevation rotators and controller connected

This step involved physically connecting the azimuth and elevation rotators to the controller with two separate 20# AWG, 6-core wires.

Firstly, the 6 m 20# AWG, 6-core wire was cut in half to form two 3 m wires. The outer insulation cover of the wire was then removed to expose the six core wires inside, roughly 0.1 m from each end, as shown in Figure 5.24 (a). The wires were then stripped to expose their conductive elements, roughly 0.02 m from their ends, as shown in Figure 5.24 (b). The 6 core wires were then crimped, Figure 5.24 (c). The same process, described with reference to Figure 5.24 (a)-(c), was followed on the other end of the same 3 m AWG wire, but this time the 6 core wires were soldered to the Yaesu 7-pin round plug, as shown in Figure 5.25 (a). Only 6-pins were connected to the 7-pin plug more specifically pin-7 was not used. The wire was then protected with a plug cap and waterproofing enclosure as shown in Figure 5.25 (b). The whole process described above was then repeated on the second 3 m 20# AWG, 6-core wire. Once both of the wires were prepared they were tested for continuity.

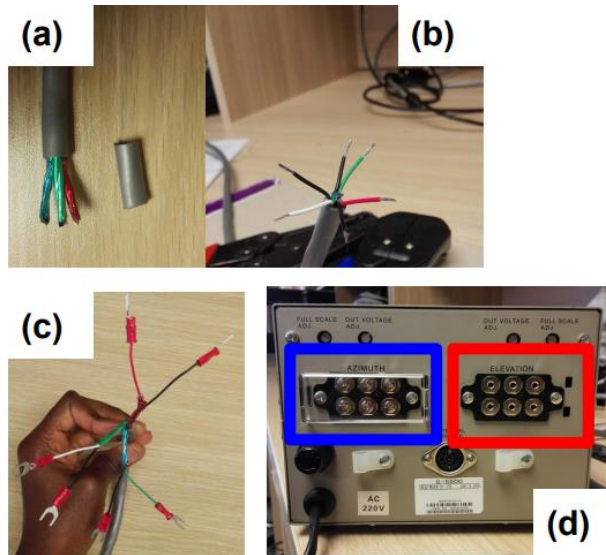


Figure 5. 24 Connecting the rotator to the control box.

After successfully passing the continuity test one crimped-wire was connected to the azimuth port, enclosed in a blue square in Figure 5.24 (d), and the other 3 m crimped-wire was connected to the elevation port of the control box, enclosed in a red box in Figure 5.24 (d).

The other end of the wire connected to the azimuth side of the control box was then connected, via its 7-pin plug, to the azimuth rotator, shown in Figure 5.25 (c) circled in blue. The same was done to the wire connected to the elevation side of the control box however, this time the 7-pin plug was connected to the elevation rotator, shown in Figure 5.25 (d) circled in red.

After these connections were completed the Yaesu rotator controller was then plugged into a wall socket rated 240 VAC @ 50 Hz. To test if the azimuth connection from the rotator to controller was successful, the azimuth controls were used to change its azimuth position. Once that was successful the same task was conducted on the elevation rotator. Both tests were successfully carried out.

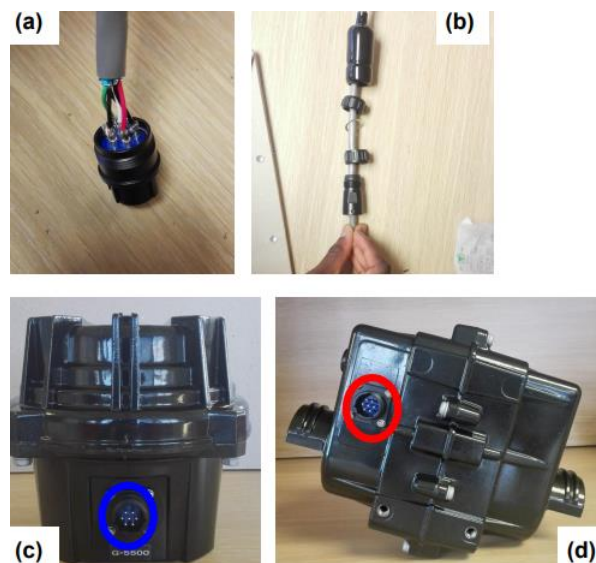


Figure 5. 25 Connecting the Yaesu G5500 plug to the rotators.

At this stage none of the parts were ready to be placed onto the structure so the ground station so the ground station at this stage still looked like Figure 5.23.

5.5.3 Mast and rotator – Clamping together with a metal clamp

This step involved clamping the elevation rotator on top of the azimuth rotator with a U-socket as shown in Figure 5.26 (a). The installed elevation rotator can be seen Figure 5.26 (b). We then clamped the azimuth-elevation unit on to the mast using a pair of clamps, shown in Figure 5.26 (c). In Figure 5.26 (c) it can be seen that each clamp has 5-holes so, the first step involved aligning the pair of clamps on either side of the mast so that their middle hole aligned with the mast's cut-out 9 mm diameter hole and their remaining 4-holes aligned with each other. Once this was accomplished the clamps were then secured onto the mast using screws, washers and nuts and then the azimuth-elevation unit was placed on top of the pair of clamps and secured onto it with screws and washers as shown in Figure 5.26 (d).

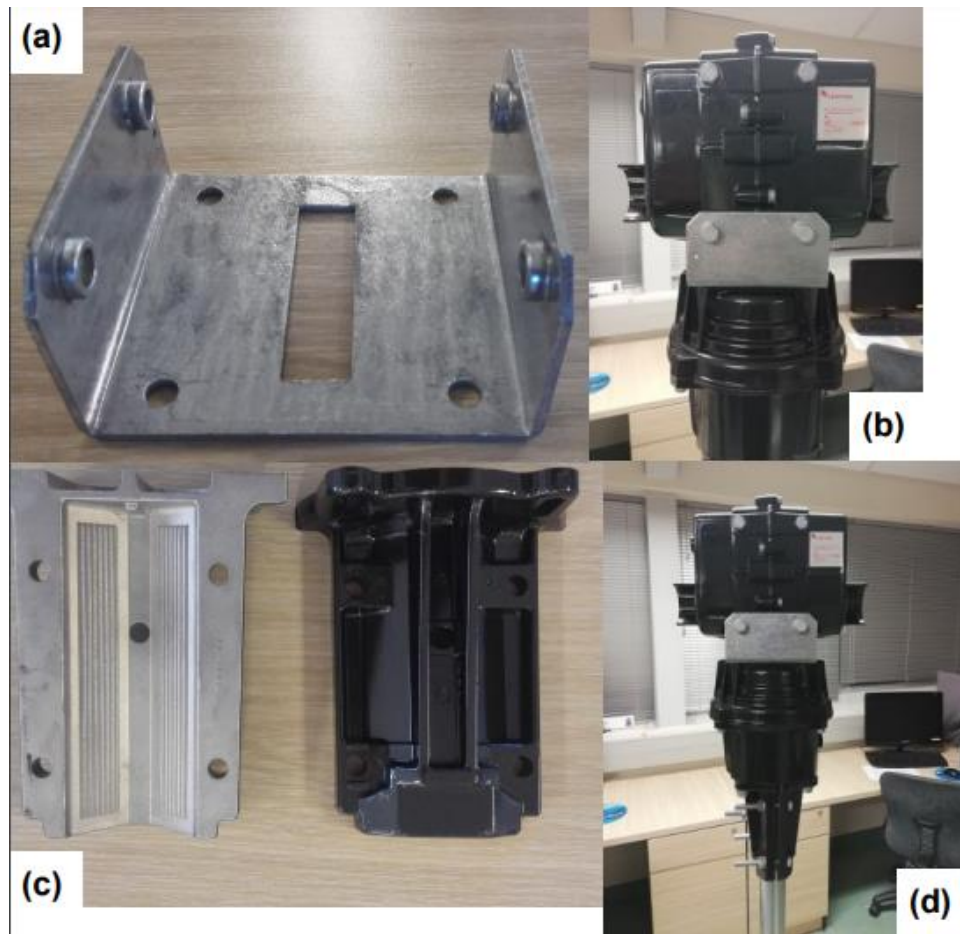


Figure 5. 26 Mounting of the azimuth and elevation rotators to the mast.

The ground station at this point looked as shown in Figure 5.27.



Figure 5. 27 An image of the Yaesu G5500 rotator mounted on the mast.

5.5.4 Antenna



Figure 5. 28 Antenna parts.

This stage involved assembling the antenna, connecting it with its phasing harness and installing it onto the crossbar. The components of the antenna are shown in Figure

5.28, as they were received from the manufacturer. Assembly follows the four steps listed below:

- Step 1: The two separate antenna booms were connected together using clamps.
- Step 2: The quad element was secured on the antenna boom with its two N-connectors under the boom.
- Step 3: In front of the quad element, 14 small director elements were secured on to the antenna boom.
- Step 4: Behind the quad element, 2 large reflector elements were secured on to the antenna boom.

After these steps were completed the phasing harness was connected to the antenna via the quad element's two N-connectors. The phasing harness, as shown in Figure 5.29(a), had one phasing line that was longer (pointed to with a red arrow in the Figure), than the other (pointed to with a blue arrow). The phasing harness was manufactured like this so that if the longest line was connected to the leftmost socket, of the balun enclosed in a white square in Figure 5.29 (b)), and the shortest line to the rightmost socket the antenna would be RHCP. Figure 5.29 (c) zooms in on the balun and indicates where the long wire would be connected with a red arrow and the short wire with a blue arrow. Reversing the connection would cause the antenna to become LHCP. For the purpose of this dissertation, the RHCP connection sequence was chosen.

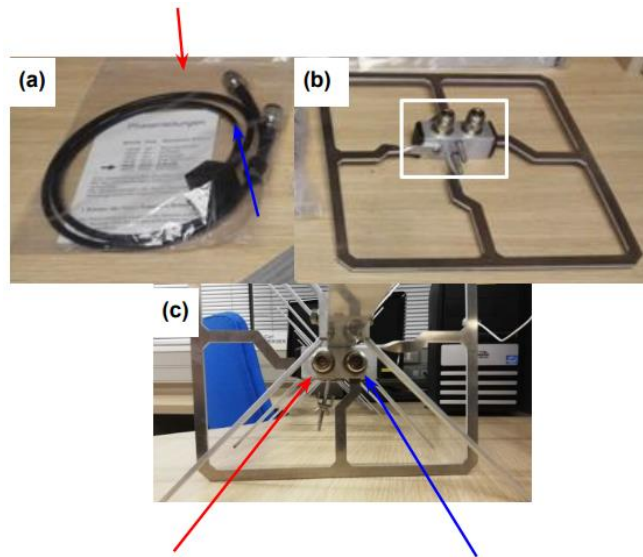


Figure 5. 29 Phasing harness connection.

The cross bar was then slid through the elevation rotator and secured with a U-bolt. Prior to installing the antenna onto the cross bar, the direction of north (0°) had to be found in relation to the SDR ground station. The software used to control the rotator uses north as its original reference point so, it was important that this was done as accurately as possible. Once the direction of north was located the antenna was secured onto the crossbar with its antenna boom facing north, as depicted in Figure 5.30.



Figure 5. 30 The SDR ground station following the installation of rotators and antenna.

5.5.5 SDR-Phasing Connection

This phase included connecting the phasing harness's SMA connector to the SDR's SMA connector, shown in Figure 5.31.



Figure 5. 31 The RTL-SDR showing in the left side its SMA connection point.

Once they were connected the SDR was plugged into a computer via its USB connection point. Prior to the SDR and phasing harness being plugged into the computer the SDR# environment was set up to accept the SDR-RTL. Once it was plugged in, the 70-cm band was scrolled through and screen shots were recorded. Next the SMA connection to the SDR was removed and the 70-cm band was scrolled through again. Screen shots were taken of the exact regions previously taken when the SDR was connected to the SDR. The images were then compared to see if there was a notable difference in signal intensity. Figure 5.32 (a) shows the frequency profile prior

to the phasing cable being connected and Figure 5.32 (b) shows the profile after the phasing harness's SMA connector was connected to the SDR. There was a notable difference and it was concluded that the connection was successful.

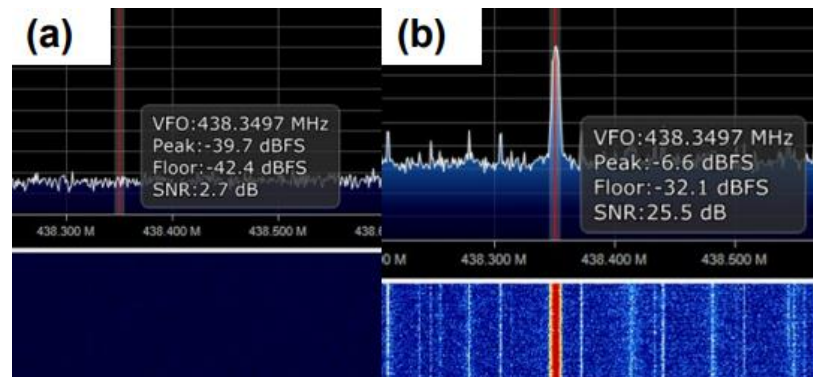


Figure 5. 32 (a) Before and (b) after the phasing harness was connected to the SDR.

5.5.6 Arduino and shield – connecting

The code used to automate the antenna rotator needed an additional daughter board, #196 proto, to be inserted on top of the Arduino, shown in Figure 5.33, so this stage involved doing just that. Prior to doing this, the shield had to be assembled. This was done by integrating its factory components, shown in Figure 5.34 (a) on the daughter board shown in Figure 5.34 (b). The factory components were tested for continuity before they were soldered onto the Vero board and the shield was again tested for continuity after being assembled. After this, the board was then modified, as shown in Figure 5.35 (b), to include the items shown in Figure 5.35 (a). These items were added to provide the board with necessary capability to control the rotator once plugged on top of the Arduino. Prior to being plugged into the Arduino and after being plugged into the Arduino continuity tests were conducted.



Figure 5. 33 The Arduino Mega 2560.

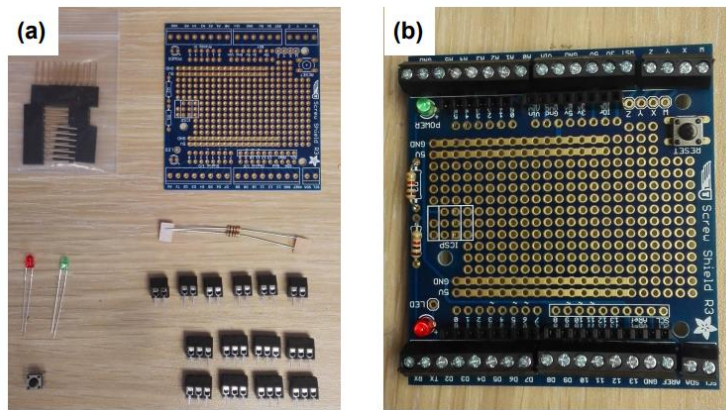


Figure 5.34 The #196 proto shield daughter board.

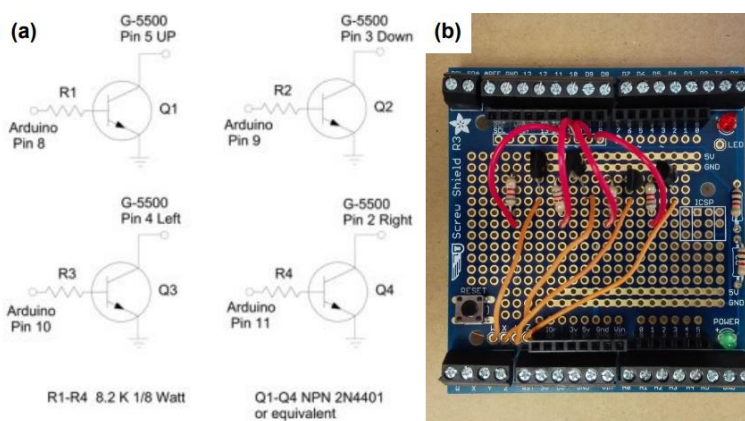


Figure 5.35 The rotator connections added to the daughter board.

At this stage none of the parts were ready to be connected to the ground station so the ground station at this stage still looked like Figure 5.30.

5.5.7 LCD circuit – building the circuit on Vero board

This stage involved making a circuit to control an LCD screen used by the rotator program to output position related values.

The circuit used to control the backlit serial display is shown in Figure 5.36. The circuit parts, prior to being connected, were tested for continuity and once the circuit was completed another round of continuity tests were conducted.

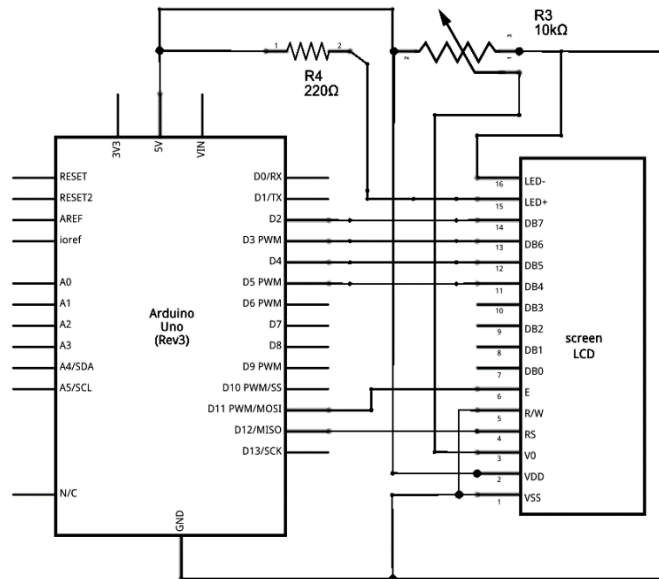


Figure 5. 36 The LCD screen circuit diagram.[105]

After the circuit was built the LCD screen circuit board was then connected to the Arduino via its shield plugs as shown in Figure 5.37.

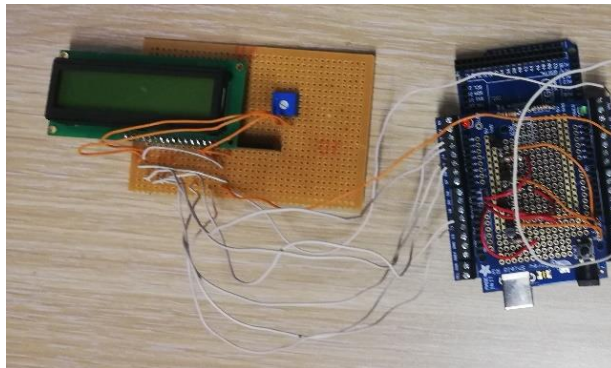


Figure 5. 37 The LCD screen connected to the Arduino and its daughter board.

Continuity tests were also conducted after this and a simple, “Hello World”, program was run to see if the screen was working as shown in Figure 5.38.

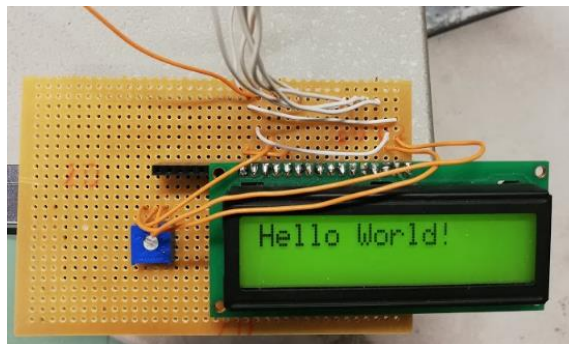


Figure 5. 38 The output seen on the LCD screen when it was tested to display, “Hello World”.

At this stage none of the parts were ready to be connected to the ground station so the ground station at this stage still looked like Figure 5.30.

5.5.8 Rotator to Arduino – soldering and connecting

This stage involved connecting the Arduino to the rotator control box. In order for the Arduino to control the control box, the Arduino board had to be connected to the external control plug circled in red in Figure 5.39. Figure 5.40 explains which pins needed to be connected and why.



Figure 5. 39 The external connection socket on the control box.

Pin	Function
6	Provides 2 to 4.5VDC corresponding to 0 to 450°
1	Provides 2 to 4.5VDC corresponding to 0 to 180°
4	Connect to Pin 8 to rotate left (counterclockwise)
2	Connect to Pin 8 to rotate right (clockwise)
5	Connect to Pin 8 to rotate UP
3	Connect to Pin 8 to rotate DOWN
7	Provides DC13V to 6V at up to 200mA
8	Common ground

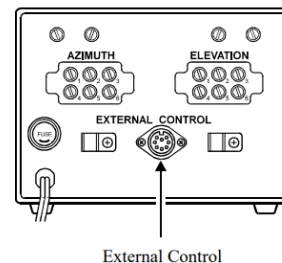
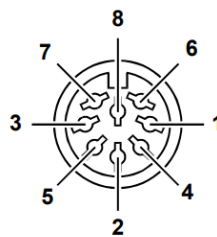


Figure 5. 40 8-pin plug connection instructions for the external control port on the Yaesu G5500 controller box.

- Step 1: Seven 0.2m wires were cut.
- Step 2: Each wire was striped roughly 0.02m from each end.
- Step 3: Each wire was then soldered on to the Yaesu external 8-pin plug. Pin 7 was not soldered with a wire. The external 8-pin plug can be seen in Figure 5.41 (a) prior to any soldering being done. The soldered version can be seen in Figure 5.41 (b) This was followed by continuity tests and the Figure 5.41 (c) shows the enclosure fitted back onto the 8-pin plug
- Step 4: Each wire was then connected to the Arduino as follows:
 - 5V on the Arduino was connected to pin 6 and pin 1 on the external pin
 - Pin 4 was connected to Arduino pin 10
 - Pin 2 was connected to Arduino pin 11
 - Pin 5 was connected to Arduino pin 8
 - Pin 3 was connected to Arduino pin 9
 - Pin 8 was connected to the ground Arduino pin.

- Continuity tests were conducted and the final Arduino-Yaesu plug installation can be seen in Figure 5.42.
- Step 5: The Yaesu plug was then plugged into its external control socket.
- Step 6: The Yaesu rotator control box's main power plug was then plugged in to the wall to test if the connections were successful. The test entailed that once the control box was switched on the LCD screen should display the current rotator position.
- Step 7: An additional test was then done to test if the Arduino could control the rotator via SatPC32. Upon connecting the Arduino to SatPC32 a visible satellite was selected at random and then the R button pressed in SatPC32 to initiate the tracking process. Once the rotator responded this stage was completed.

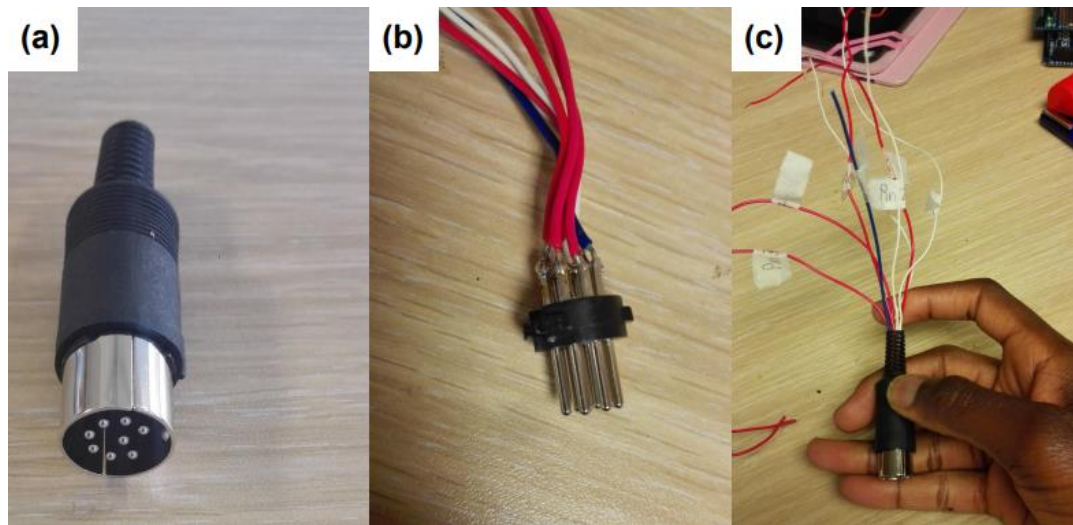


Figure 5. 41 The external plug being constructed.

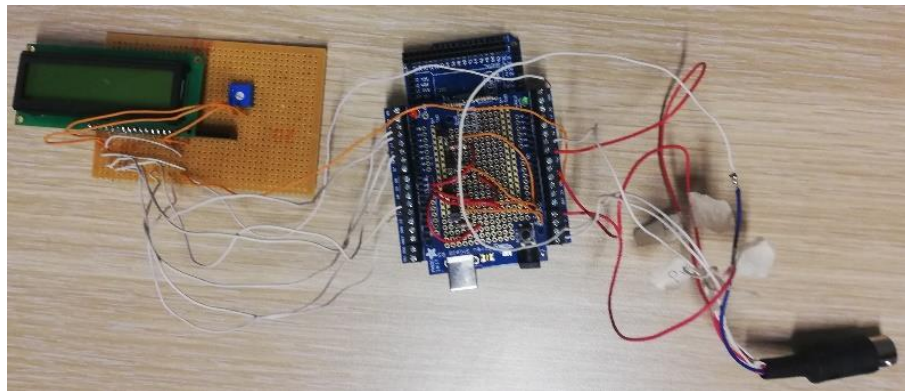


Figure 5. 42 The external plug connected to the Arduino and its daughter board.

With these connections, the assembly of the ground station was completed. The final SDR ground station looked like the image presented in Figure 5.43.



Figure 5. 43 The completely assembled SDR ground station.

6 COMMISSIONING TESTS AND RESULTS

This Chapter discusses the activities that were conducted to test if the developed SDR ground station could receive packets from at least one small satellite in LEO. We begin with a discussion of the operation flow of the ground station. The environment in which the tests were conducted is then described. The tests are then presented with their results.

6.1 SDR Ground Station Operation Flow

This section explains how the SDR ground station was designed to operate. A block diagram is provided in Figure 6.1 and explained below. The operational steps assume that all the software applications are opened and that the Arduino and shield have been compiled with the appropriate rotator controller software.

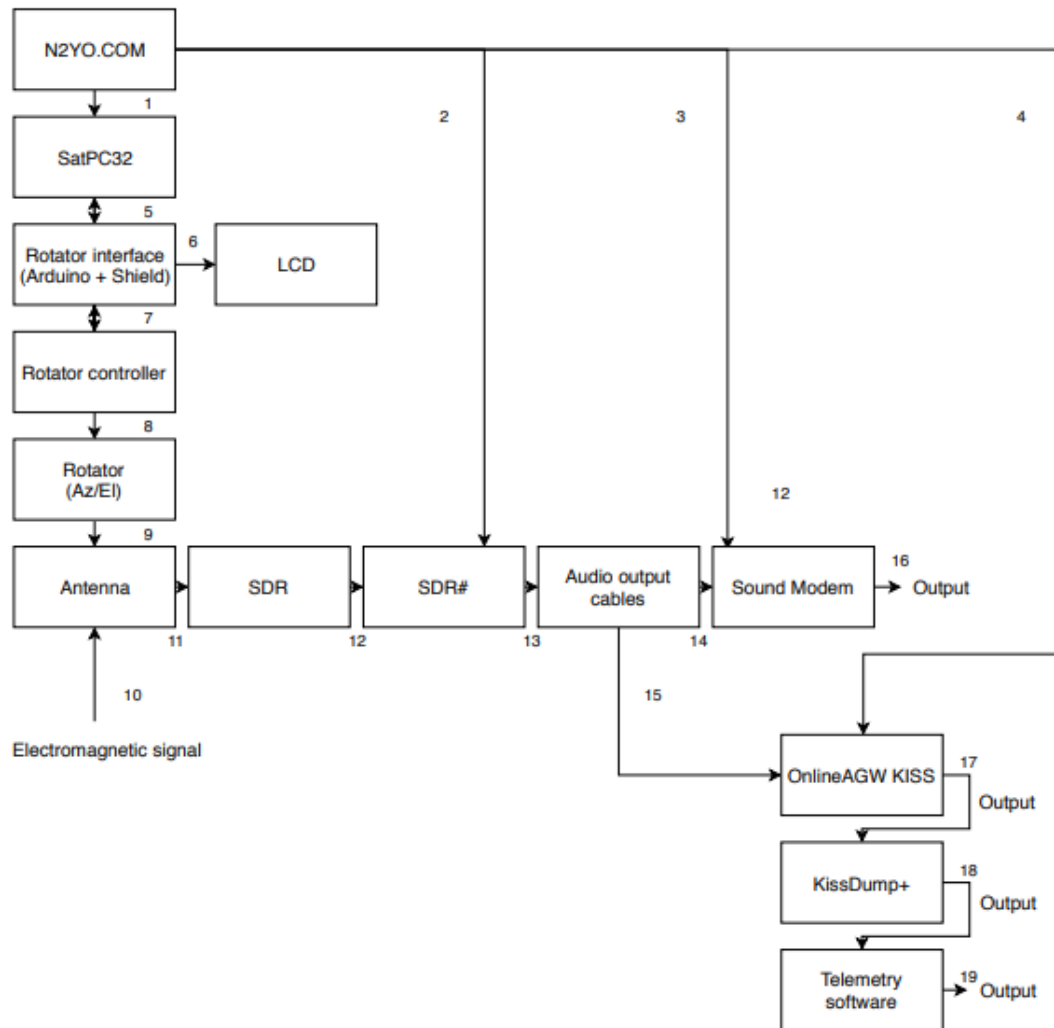


Figure 6. 1 SDR ground station flow diagram

The operations flow depicted in Figure 6.1 is explained through an example. For the ground station to track a small satellite in LEO the operator of the ground station would need to visit N2YO.com to figure out when the satellite would be in view of the ground station; the satellite's downlinking frequency; its call sign and mode. Once that is done, the call sign and name of the satellite should be used to select the satellite that needs to be tracked within SatPC32 (1). The downlinking frequency should be used to tune SDR# to the downlinking frequency (2); the mode should be set in Sound Modem so that it can properly receive the incoming signals (3) and lastly the name and or call sign should be used to command AGW Online KISS (4) to store the incoming packets, of the particular satellite being tracked, to a file named after it.

Once SatPC32 is set up it can then be commanded to track the particular satellite of choice. The command to track the satellite gets sent to the rotator interface and the rotator interface in turn communicates its state back to SatPC32 (5). The result of the back and forth communication between the interface and SatPC32 should be reflected in the LCD screen (6) and rotator controller (7). The LCD screen should display SatPC32's azimuth and elevation values and the rotator controller should do the same in addition to it commanding the rotator (8) to move in accordance with the values it

receives from SatPC32 via the rotator interface. If that is successful, the rotator should be able to influence the antenna's (9) position based on its motion.

Once the antenna is tracking the particular satellite's motion it should be able to receive signals from the satellite (10). Incoming signals will then be directed into the SDR (11) where they can be converted from analogue to digital signals. Once that is accomplished the signals then pass into SDR# (12) where they can be scrutinized and processed in various ways. The audio related to the incoming would then be guided into the virtual output audio cables provided by VAC (13). The audio passes through the virtual audio cables so that they can be processed through Sound Modem (14) and AGW Online KISS (15). Sound Modem has the ability to decode and display incoming packet in ASCII (16). Packets that cannot be decoded by Sound Modem, based on their format, can to be decoded in AGW Online KISS. In AGW Online KISS the incoming packets get transformed into Hex code and stored in KISS files (17). The KISS files can be displayed for scrutiny in Kiss Dump (18), if need be. The Hex KISS files can also be decoded using telemetry software, if it is available. The telemetry software has the ability to make sense of the received information by displaying the input data in readable fields (19), as shown in Figure 6.2.



Figure 6. 2 An example of a telemetry decoder.[106]

6.2 Test Environment

The Commissioning tests were conducted in the SpaceLab, as shown in Figure 6.3, because of rooftop safety issues at the University of Cape. The following attributes describe the SpaceLab's environment:

- Altitude: 120 m above sea level.
- Ceiling: Thin suspended ceiling under a pitched clay tile roof.
- Windows: Glass, open and wide windows without burglar guards.

The SDR ground station was positioned near windows and during tracking episodes the windows in the lab were opened to decrease the number of obstacles between the incoming signals and the ground station. The floor where the ground station was positioned was assessed with a level to make sure that the SDR ground station was level in order to accurately track satellites with minimum deviation.

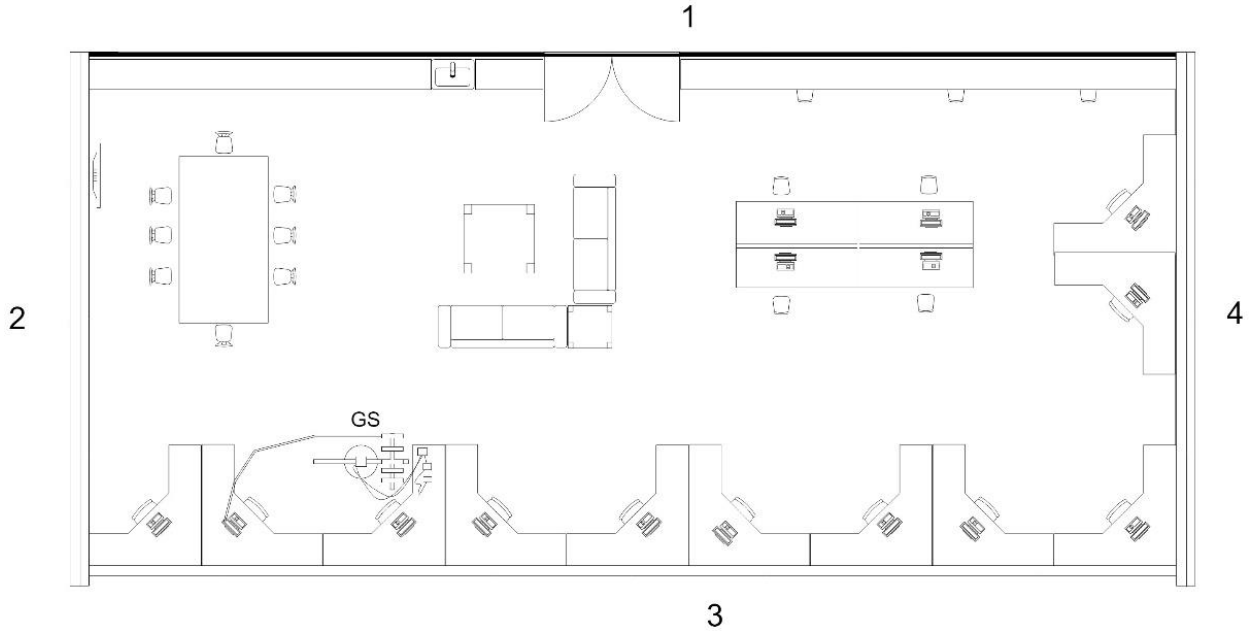


Figure 6.3 Plan of the SpaceLab showing the location of the ground station (GS) antenna during these commissioning tests.

Figure 6.3 shows a plan of the SpaceLab, with the location of the ground station marked with “GS”. Whenever the antenna pointed towards the wall labelled “1”, tracking was stopped because a significant number of offices were stationed behind wall “1”. The rest of the side of the SpaceLab are enclosed by large windows as seen in numbers 2-4. However, there is a large mountain behind “4” so tracking was also limited in this area. The only reliable passes were viewed and recorded on side “2”, “3” and when the antenna pointed towards the ceiling. In view of this, some satellites were not tracked based on the positioning of the ground station. The lab however was advantageous because it had wall power that was readily available and there were no wind effects on the SDR ground station.

6.3 Tests and Results

This section documents three notable satellite tracking sessions. Each test tracked a different satellite. Before the results of the test are presented the relevant satellite’s, information is presented.

The question each test aimed to prove was:

- Is the SDR ground station able to make contact with a small satellite in LEO?

“Contact” within the confines of this dissertation can be defined as:

- Physical satellite data (Small satellite packets)
- Audio (Small satellite Continuous Waves (CW))

To substantiate and explain the results, results from other amateur radio ground stations were acquired over the internet. The outputs are described, and each test is assessed to see if it was successful or not.

All the tests were conducted in the in the same manner outlined in the operations flow described in section 6.1. This section assumes that the following tasks were conducted prior to each test being conducted:

- The Arduino and shield were compiled with the necessary code.
- SatPC32 was set up with the appropriately for the satellite it was monitoring.
- AGW Online KISS was set up appropriately for the satellite it was monitoring.
- SDR# was tuned to the correct frequency for the satellite it was monitoring.
- Sound Modem was set up appropriately and tuned to the correct mode for the satellite it was monitoring.
- Rotator controller was electrically switched on.

6.3.1 Test 1: SK-CUBE

The first test that was conducted aimed to track SK-CUBE, whose information in presented in Table 6.1

Table 6. 1 Details used to track SK-CUBE, 2018/12/18

Aspect	Value
NORAD ID	42789
Int'l Code	2017-036AA
Perigee	497.2 km
Apogee	514.6 km
Inclination	97.4 °
Period	94.6 minutes
Semi major axis	6876 km
RCS	UNKNOWN
Launch date	June 23, 2017
Source	Slovakia (SK)
Launch site	SRIHARIKOTA (SRI)
Downlink	437.100/2401.000
Mode	9k6GMSK Digi-peater CW
Call Sign	OM9SAT
Status	Active

The first feedback that was recorded when SKCUBE was tracked was the wave form present in SDR#. Two images are presented in Figure 6.4. The one on the left-hand side, (a), is the observed wave form and the one on the right-hand side, (b), is what a SKCUBE wave form is meant to look like. The RF FFT graphs have a similar parabolic shape, however the RF waterfall graphs were not similar. The observed RF waterfall had a longer impulse than the waterfall graph on the right.

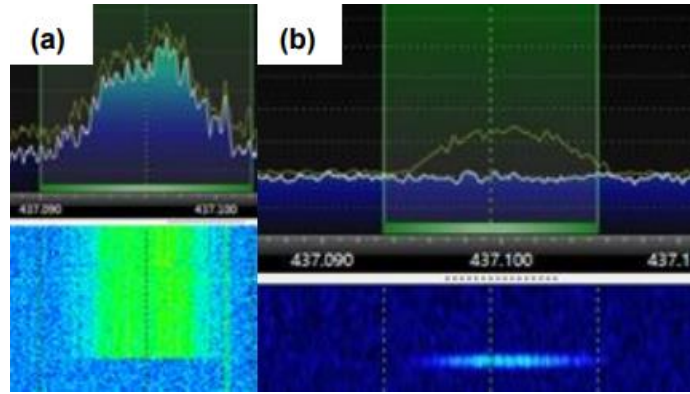


Figure 6.4 (a) What the wave form should look like versus (b) the SDR ground station's output.

The next output that was evident during this tracking session was the output from Sound Modem. Figure 6.5 shows what Sound Modem observed and Figure 6.6 shows an observation from radio amateur radio enthusiast @w2rtv1. Fig 6.5 shows that AX25 packets were successfully received and decoded into “NON-AX25” frames. Since the incoming packets were AX25 packets, Sound Modem could not decode their information directly, so the decoding was done by AGW Online KISS. The decoded information, displayed in KISSDump+, can be seen in Figure 6.7. Comparing the decoded ASCII information found in Figure 6.5 with the decoded ASCII information, shown in green in Figure 6.6, it was evident that they did not resemble each other. In addition to this there was no identifiable information in Figure 6.5 that stated that the packet came from SKCUBE as compared to Figure 6.6. Figure 6.6 clearly states that the packet was sent by “OM9SAT”, SKCUBE’s call sign.



Figure 6.5 The SDR ground station's Sound Modem output for SKCUBE.

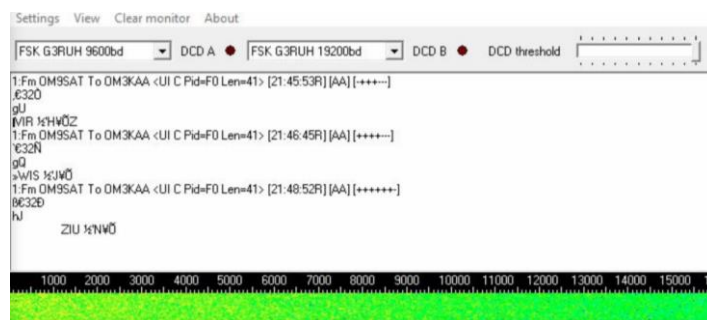


Figure 6.6 A Sound Modem output from @w2rtv1 for SKCUBE.

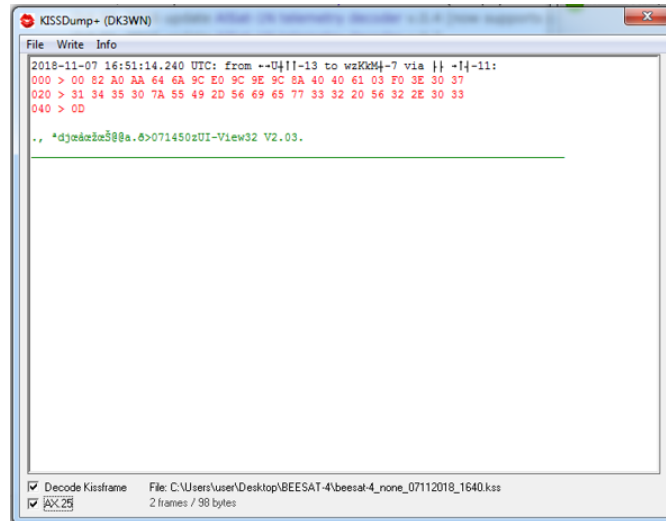


Figure 6.7 The KISSDump+ output in Hex code and in ASCII.

Based on the information acquired through the first test this test was considered unsuccessful. The observed waveform, sound modem output and AGW Online Kiss decoded output displayed on KissDump+ were not in alignment with the intended results. The test did however show that packets from an unconfirmed source were received and decoded proving that the ground station was able to receive signals from a source from outside the SpaceLab.

6.3.2 Test 2: CSSWE7

The next test that was conducted aimed to track the CSSWE7 satellite, whose information is presented in Table 6.2

Table 6. 2 Details used to track CSSWE7, 2018/12/18.

Aspect	Value
NORAD ID	38761
Int'l Code	2012-048-D
Perigee	502 km
Apogee	739 km
Inclination	64.670
Period	1 h 37 m 07s (97.12 min)
Semi major axis	6 999 km
Downlink	437.345 MHz
Mode	9k6 FSK AX.25
Call Sign	CSSWE7(Colorado Student Space Weather Experiment)
Status	Active

Figure 6.8 shows the output that appeared on the Sound Modem screen and the Figure 6.9 shows an output acquired from Mineo Wakita, a JAMSAT member, who observed CSSWE7 in 2014.



Figure 6. 8 The SDR ground station's Sound Modem's output for CSSWE7.

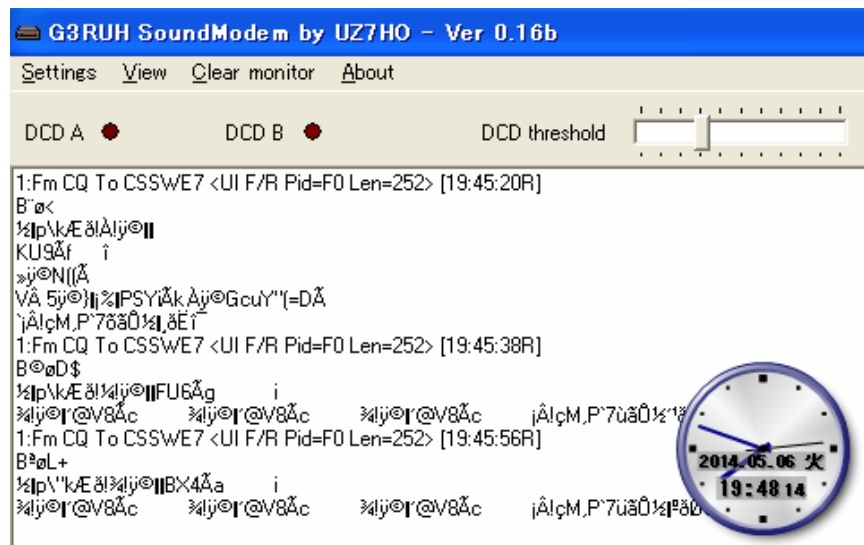


Figure 6. 9 A Sound Modem output from Mineo Wakita for CSSWE7. [107]

Figure 6.8 shows that NON-AZ25 packets were received because Sound Modem was able to decode the packets successfully without AGW Online KISS.

The first lines in Figure 6.8 and Figure 6.9 read as, “1:Fm CQ To CSSWE7”, instead of, “Fm CSSWE7 To CQ”. According to Mineo Wakita the order was been reversed by mistake because of the way the satellite’s beacon was formatted coupled with the fact that Sound Modem is still in its experimental phase. [107]

Another similarity between the images in Figure 6.8 and Figure 6.9 was their packet lengths. They both had the same length of 252. The time intervals in which the packets were received differed in both output and the decoded text is slightly different in

certain sections, which is okay because the observations happened on different days and at different times.

The results presented in this section showed that the SDR ground station was able to make contact with CSSWE7 in the form of packet reception. The received packets were decoded and displayed in ASCII in Sound Modem. They took on a similar structure as compared to an output from JAMSAT member, Mineo Wakita. This test was marked as successful.

Since the packets were decoded in Sound Modem and not in AGW Online KISS the frames were not stored in KISS files and could not be further processed by satellite specific decoders.

6.3.3 Test 3: RAX-1

The next test that was conducted aimed to track RAX-1, whose information is presented in Table 6.3

Table 6.3 Details used to track RAX-1, 2018/12/18. [108]

Aspect	Value
NORAD ID	37223
Int'l Code	2010-062B
Launch date	November 20, 2010
Source	United States (US)
Launch site	Kodiak Island, Alaska (KODAK)

The following screen shot, shown in Figure 6.10, was taken from the output displayed on Sound Modem.

1:Fm RAX-1 To CQ <UI R Pid=F0 Len=235> [18:42:06R] [AA] [+-----]
«lěnvJQjJQ ŷŷ5'A MZŠ'zqyylqM6auillaÆæÿPp k'ay
ŷ3±ñ fēÜ RhC¹-o5'''b Æ 5lf8Łŷŷł†XWWYZZZ.İÇYLëFryZYİÊĖA BŸŷŷŷÖŷŷŷŷŷŷŷŷ hŸŷŷ

1:Fm RAX-1 To CQ <UI R Pid=F0 Len=235> [18:42:07R] [AA] [+-----]
«lěnvCEJQ±JQ ŷŷ4-{ Pž.
ŚnnŷŷlnM5dAI.BÄŽç.«ŷ'pŞk''ayŷ@—
ÄLlä'š^A'G' 'dyČ ħEƒ8Łŷŷł†XWWYZZZ.İÇYLëFryZYİÊĖA BŸŷŷŷÖŷŷŷŷŷŷŷŷ hŸŷŷ

1:Fm RAX-1 To CQ <UI R Pid=F0 Len=235> [18:42:08R] [AA] [+-----]
«lěnv—JQ»JQ ŷŷ4*f MZŠ'~snŷŷlnN6fG pÄYe=yėp 8(k''ayŷŷ8'3<^
® OfĂ.Â.'™še Æ wAf8Łŷŷł†XWWYZZZ.İÇYLëFryZYİÊĖA BŸŷŷŷÖŷŷŷŷŷŷŷŷ hŸŷŷ

1:Fm RAX-1 To CQ <UI R Pid=F0 Len=235> [18:42:09R] [AA] [+-----]
«lěnvıJQAJQ ŷŷ5— MZ&&ħnŷŷloN4huş)BÄđe_ŷəp' k''ay&ŷ''vı)s%\$.\$Ė[6á«ı≠İÇ
x>ƒ8ŁŷŷĚÇXWWYZZZ.İÇYLëFryZYİÊĖA BŸŷŷŷÖŷŷŷŷŷŷŷŷ Ad^ħhŷ

1:Fm RAX-1 To CQ <UI R Pid=F0 Len=235> [18:42:11R] [AA] [+-----]
«lěnvŁJQäJQ ŷŷ4"" Pž(loŷŷĖNMTöüDĞÄ''ıkŷ baeŷL"k'ayÆpNŞZ *@ďF.@>
äZâ½±«°j»Æ Ü=f8ŁŷŷÇĐ«XWWYZZZ.İÇYLëFryZYİÊĖA BŸŷŷŷÖŷŷŷŷŷŷŷŷ UhŸŷŷ

Figure 6. 10 The SDR ground station’s Sound Modem output for RAX-1.



Figure 6. 11 A Sound Modem output from Mineo Wakita for RAX-1.[107]

Figure 6.10 shows that NON-AZ25 packets were received because Sound Modem was able to decode the packets successfully without AGW Online KISS.

It can be seen that contact was made with RAX-1 from the first line as pointed out in Figure 6.10. This same attribute is shown in Figure 6.11, a result captured by Mineo Wakita. The length of the packets received is different, however this difference is acceptable because the length of the frames could have been affected during transmission. In both screenshots the decoded information is shown in ASCII text and looks similar.

Since the packets were decoded in Sound Modem and not in AGW Online KISS the frames were not stored in KISS files and could not be further processed by satellite-specific decoders.

Based on the screenshots shown above, this test was deemed to be successful. The SDR ground station was able to make contact with RAX-1 by receiving packets. It was also able to decode the packets and present them in an ASCII format. This test definitively showed that the SDR ground station was able to make contact with a satellite in LEO.

Test 3 concluded the commissioning tests for the SDR ground station. The next chapter deals with conclusions related to the tests, results and recommendations for future work and improvements to the SDR ground station.

7 CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes this dissertation and it provides recommendations as to how the SDR ground station could be improved upon. The conclusions and recommendations are both based on the mission's objectives, requirements and constraints.

7.1 Conclusions

The mission's objectives, requirements and constraints are displayed in this section to demonstrate that they were all met through the final SDR ground station. The most important criterion was the primary objective shown in Table 7.1.

Table 7.1 Achievement of primary, secondary and hidden objectives.

Type	Objective	Achieved	Comment
Primary	Design, develop and build a low cost, portable and expandable SDR ground station to establish communication (to listen, receive and decode) with LEO small satellites operating in the 70-cm band.	Yes	The final system was under budget; semi portable; houses equipment that can be extended upon and the system was able to make contact with RAX-1 and CSSWE7, two small satellites in LEO.
Secondary	Data sharing.	Yes	Information is freely available for anyone to use.
	National and international cooperation.	Yes	Insight from 1KUNS-PF team, Deon Coetzee (AMSAT SA)
	Participate in and contribute to national/international projects.	Yes	It has the ability to support national and international projects.
	Support future SpaceLab missions.	Yes	Students working on satellite tracking related projects could use the system.
Hidden	Highlight SpaceLab's capabilities.	Yes	The SpaceLab now has a working 70-cm band SDR ground station.

The operational requirements are displayed below in Table 7.2 in relation to the SDR ground station. All of the operational requirements were met.

Table 7. 2 Achievement of Operational Requirements.

Operational	Achieved	Comment
Tracked satellites shall be located in LEO.	Yes	The system made contact with RAX-1 and CSSWE7.
The system should be able to store downlinked data automatically.	Yes	The packets received all get stored on the computer's database once they are received.
The SDR ground station should be able to track a satellite intermittently for a maximum of 3 minutes	Yes	The Yaesu G5500 allows the system to track satellites for up to 5 min at a time and requires 15 min breaks between operations.
Satellites operating in the 70 cm band (UHF, 430-440MHz).	Yes	The antenna is rated to work in the 430-440Mhz range.

Table 7.3 presents the functional requirements associated with the final SDR ground station. Both functional requirements were met through the SDR ground station.

Table 7. 3 Achievement of Functional Requirements for the SDR Ground Station.

Functional	Achieved	
The system should be able to track one small satellite at a time.	Yes	The application used to help track satellites, SatPC32, has the ability to only track one satellite at a time.
The SDR ground station shall be able to at least decode one type of the data (sound, packets) it receives into another form.	Yes	The SDR ground station was able to decode ASCII received information into Hex.

Lastly, the SDR ground station's constraints were assessed. The weight/portability constraint was partially met, and the rest of the constraints were fully met in Table 7.4

Table 7. 4 Achievement of objectives within the specified constraints.

Constraint	Explanation	Achieved	Comment
Cost	The total cost of the SDR ground station shall be below R20000.	Yes	The total cost of the SDR ground station was R1XXX.
Schedule	The SDR ground station shall be operational within one year (365 days).	Yes	The SDR ground station was built and commissioned within a an 11-month period from February 2018-December 2018.
Regulations	The SDR ground station shall not be able to uplink a single signal.	Yes	The SDR does not have up-link capabilities.
Interfaces	All control interfaces of the SDR ground station shall be able to be operated by one computer.	Yes	The ground station only has one computer that is able to facilitate signal acquisition and processing.
Environment	The SDR ground station should be rated to withstand a wind speed of 5 m/s at its centre of mass.	Yes	The SDR ground station was designed to withstand a wind speed of 5m/s.
Portability/ Weight	The system shall have a mass of less than 50 kilograms.	Partially	The ground station mass is approximately 41 kg. It can easily be dismantled and taken to different locations. It is however dependent on a power source so that limits its portability.
Automation	Tracking shall be automated.	Yes	The SDR ground station's rotator is completely controlled by an Arduino; its daughter board and computer
Height	The SDR ground station should be under 2m in height.	Yes	The SDR ground station is under 2m in height, under all antenna configurations.
Power	The SDR ground station only house equipment that is rated 230 V / 50 Hz or lower.	Yes	The only item in the ground station that is dependent on power is the rotator controller. It requires power within the range of 220-240V @ 50Hz.

All the attributes were achieved, except one which was partially achieved. Based on this, the final SDR ground station was able to not only meet its primary goal, but it was able to satisfy the secondary objectives, requirements and constraints.

7.2 Recommendations for future work

The recommendations outlined in this section are directly linked to the SDR ground station; the way it was designed and constructed. The following aspects will be discussed:

- LNA
- Partnerships
- Testing

- Locations
- Remote access
- Compass
- Enclosures

7.2.1 LNA

An LNA could be added into the design of the SDR ground station for better signal reception. It was originally taken out to curb costs and because signal reception was possible without it. However, the addition of an LNA could improve the design by strengthening weak signals from satellites that the ground station wasn't able to pick up. The effects of noise on very weak signals reduced the possibility of them being detected on the SDR# display. In addition to this, the inclusion of the LNA would result in the entire SDR ground station being under R20 000, if the LNA4All were to be purchased.

7.2.2 Partnerships

Partnerships with more small satellite teams should be made. This dissertation included input from the 1KUNS-PF ground station team. They were able to provide useful design information and guidance. More partnerships would contribute positively to the current SDR ground station design and operation. In addition to this, partnerships would ensure that the downlinked information would be decoded and utilized in an appropriate manner. It could facilitate national and international endeavours and increase the rate of knowledge sharing amongst local and international teams.

7.2.3 Testing

Establishing contact with a satellite can take several attempts. Factors such as the weather, distance, timing and track of passes, and noise influence the ability to make positive contact with satellites in LEO. Therefore, it is advised that the testing period given to any future improvements should be at least 2 months.

7.2.4 Operating Locations and Conditions

The SDR ground station needs to be tested in different locations to measure its efficiency under different circumstances and operating conditions such as: altitude, terrain and weather. In addition to this, theoretically the ground station can handle 5m/s wind, however this has not been proven in practice. Testing this is important for any applications where the ground station would be deployed permanently outdoors. Should wind-shake prove to be a problem, consideration could be given to housing the antenna in a structure that is transparent to RF signals.

7.2.5 Remote Control and Automation

The SDR ground station would benefit greatly if it could be controlled remotely using an application running on a mobile device, such as an Android cell phone. Remote

control would allow the operator to not have to be stationed directly at the ground station in order to operate it; save downlinked information for future processing purposes; monitor satellites for other organizations given short notice and to even check the SDR ground station's vital signs, to mention a few. Once the ground station's operations prove to be reliable, they could be automated such that the ground station could automatically track and receive signals from a list of satellites, without any operator intervention.

7.2.6 Enclosures

The Arduino, its shield and the LCD screen would benefit greatly if they were housed in durable enclosures. The SDR ground station is meant to function as a portable base but these pieces may get damaged during transportation if they are not carefully packaged during transportation. Ruggedized enclosures for these items would lessen the risk of damage and the need to pack the equipment very carefully during transportation.

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APPENDICES

APPENDIX 1 SOUTH AFRICAN RADIO AMATEUR EXAMINATION (RAE) LICENSE INFORMATION [109]

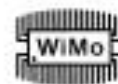
Aspect	Explanation
Licenses	<p>There are two types of licenses Class A and Class B.</p> <p>a) Class A: An internationally acknowledged license with complete rights and benefits set out in the South African Radio Regulations. Successful candidates will end up with a Harmonized Amateur Radio Examination Certificate (HAREC)</p> <p>a) Class B: Can be legally held until the age of 25 years old but can only be attained at the age of 20 years old or younger. Successful candidates will end up with an Amateur Radio Station License Introductory Level certificate. This license becomes obsolete once the carrier reaches 25 years old. In order to continue to operate as an amateur radio participant one must write the Class A examinations.</p>
Examined Sections	<p>In the RAE examinations there are two sections presented in one paper:</p> <p>a) Regulations and Operating Practices b) Technical (Theory)</p> <p>Prior and in addition to completing the RAE participants must pass a practical operating test in order to get a High Frequency (HF) Operating Assessment Certificate</p>
Examination	<p>A participant must first successfully complete and submit their practical examination results in order to qualify to write the RAE. A participant may be granted permission to submit their practical results with the RAE answer paper in exceptional cases.</p>
Examiners	<p>The examinations are conducted by the South African Radio League (SARL) on behalf of the Independent Communications Authority of South Africa (ICASA). Only an official SARL assessor is allowed to conduct examinations</p>
Pass mark	<p>In the RAE examination:</p> <p>a) Regulations and Operating Practices - (minimum of 50%) b) Technical (Theory) - (minimum of 50%)</p> <p>An overall pass mark of 65% which include the RAE and the practical section.</p>

License jurisdiction	<p>a) Class A: Based on the European Conference of Postal and Telecommunications Administrations (CEPT) so it is valid in most European countries and other non-CEPT member countries</p> <p>b) Class B: An introductory level license only valid in South Africa.</p>
Dates	Normally held between 10am- 1pm on a Saturday twice a year in May and October.
Material	Material freely available for download on the SARL website. Classes are offered in major cities at a cost and participants can chose to enrol independently.
Cost	<p>a) Class A: R500 (R400 for persons under 25 years old)</p> <p>b) Class B: R400</p>
Additional	<p>a) All license costs</p> <p>b) ICASA radio license fee for the first year</p> <p>c) Complimentary SARL membership</p>

APPENDIX 2 THE X-QUAD ANTENNA AND PHASING HARNESS'S MANUAL AND SPECIFICATION DOCUMENT [87]



- 7 -



X-Quad

Directional antennas for 2m or 70cm with switchable polarisation

☐ 2m No. 18010

☐ 70cm No. 18011



**Description
Assembly
Adjusting**

WiMo Antennen und Elektronik GmbH

Am Gäxwald 14 D-76863 Herxheim
<http://www.wimo.com>

Tel.(07276) 96680 FAX: 966811
e-mail: info@wimo.com

- 8 -

Description

The X-Quad is a step forward basing on the well known boom quads. Its specially for amateur radio use designed properties are:

- Polarisation is switchable (horizontal / vertical / zirkular right / zirkular left / diagonal)
- high gain in comparison with other antenna system through stacking effects
- short boom and simple construction
- Foremast mounting

The radiator is a stacked quad element. Compared to cross yagis all passive elements of a X-Quad (e.g. directors, reflectors) are active elements which leads to high gain at compact size. Changing the antenna's polarization (HV) is easily accomplished by choosing the proper feedpoint.

Polarizaion switching is done with a coax relay or with one our our remote-control polarisation switches mounted near the antenna feed point, requiring a short feed line only.

With our special phasing harness the antenna can be configured for fixed circular polarisation, see the table below.

All elements and the shield of the feedline are grounded, avoiding any problems with electrostatic discharge.

The connection of the both feeder lines is to be done with N-connectors, the case is waterproof sealed.

Boom and elements are fully made of aluminum. All screws, nuts, washers and the U-bolt of the mast clamp are made of stainless steel and guarantee good contact and easy handling even after years on the roof.

The antenna design and make is protected under german patent law.

Technical Data

	3m X-Quad	70cm X-Quad	
elements per plane	12	18	
gain	10,5	12,8	dBD
3-dB bandwidth horiz. (E)	47	36	degrees
vert. (H)	47	36	degrees
F/B ratio	19	21	dB
max. power	1500	1000	Watt
length	1460	1270	mm
height	730	220	mm
weight	2,3	1,6	Kg
wind load (@ 160km/h (100mph)	74	48	N
connector	2xN-Jack	2xN-Jack	
stacking distance	2,82	1,1	m
phasing harness for RHCP or LHCP	18047	18049	
part no.	18010	18011	

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Mounting

- Assemble the boom with 2 boomjoints, screw M6x35, lock washer, big washer M6 and lock nuts.
- Mount the radiator fully: loosen the 2 screws on the outside of the lower part of the radiator and re-screw them after the upper part is set on the lower part of the radiator. The 70cm X-quad is delivered with a complete assembled radiator.
- Remove the 2 nuts M5 on the bolts of the connector case. Should you find any rubber seals, please remove them too, they are not needed any more.
- put the radiator on the boom and fix it with the nuts removed in step before. the connectors have to point backward (short side of the boom). the loose end of the radiator is to be fixed with a self tapping screw.
- Mount the reflector and director elements with the element clamps provided. 2 elements are mounted together with one screw. Take care about the different element lengths: the 70cm X-Quad has only one director length, the reflector element is longer. The 2m X-Quad has 3 different element lengths: the reflector is the longest, the first director (nearest to the radiator) is shorter, the other 3 directors are the shortest with same lengths.
- Mount the mast clamp: the antennas are made for foremast mounting, the clamp will be mounted behind the reflector element. Take care, the 2 N-jacks must be side by side, not above each other after the antenna is mounted to the mast. When a glassfibre tube is used, the clamp may be set into the middle of the boom.

Each plane has its own feedline, when the antenna is mounted with both jacks facing downward to the rear (connector case under the boom), the left N-jack is the horizontal plane and the right N-jack is the vertical plane. See figure below.

Usually N-connectors are waterproof when they are mounted correctly. Anyway it's helpful to seal the connectors with self amalgating tape no. 23065.

Adjusting

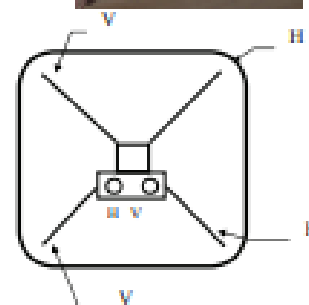
Normally the antennas don't require any adjustments. For fine tuning of SWR the ends of the first director must be bended. Always bend both ends of the director like shown in the figure below. Bended to radiator: the resonant frequency shifts downward, bend to second director the frequency shift upward. Take care to use the right ends of the director, the adjustments of the 2 planes effect each other a bit.

As the bending is not easy to do, you may twist the flat material 90° like shown in the picture. afterwards adjustments are much easier.



parts list

	part No.	2m-XQuad	70cm-XQuad
1	boom	1	1
2	radiator element complete	1	1
3	passive elements	10	16
4	mast clamp	1	1
5	fixed clamp	1	1
6	clamp for boom 20mm	1	1
7	U-bolts	1	1
8	element holder	10	16
9	DIN 84 screw M5x35	5	8
10	DIN 933 screw M6x12	2	2
11	DIN 7981 self tapping screw 3,5x9,5	1	1
12	DIN 127 lockwasher 5mm	7	10
13	DIN 127 lockwasher 6mm	4	4
14	DIN 9021 washer 6mm big	4	4
15	DIN 934 nut M5	7	8
16	DIN 315 wing nut M6	2	2
17	description	1	1
18	boomjoint (u-shape)	2	2
19	DIN 933 screw M6x12	2	2
20	DIN 985 lock nut	2	2



Seen from back of the antenna: right jack is the vertical connector. For adjustment of SWR in vertical plane, bend the left ends of the first director to front or back of the antenna.

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- When the X-Quads shall be used with fixed right hand circular polarisation both planes are to be connected with a phasing harness. This harness is to be connected directly to both antenna feedpoints and is made of different cables with different lengths. There is only one feedline required. This solution is cheap, but fixes the antenna to either RHCP or LHCP. It is not possible to use the antenna with linear polarization. We provide plug-and-play phasing harnesses, see the picture to the right.
- When the polarisation shall be switchable, our polarisation switchbox can be used (only available for 2m). Two feedlines running down the mast are required with exactly the same length. A short jumper is required between switchbox and transceiver. The switching is done manually with the rotating switch of the box.
- For remote-controlled switching we provide different switches for mast mounting. Those switches come in waterproof boxes and are controlled by a normal DC wire. The antenna connection is done with 2 short cables and there is just a single feedline down to the shack.



switchable polarisations:

	remote polarization switch	remote antenna
vertical	X	X
horizontal	X	X
RHCP	X	-
LHCP	X	-

Connecting our phasing harnesses.

The antenna must be assembled with the N-jacks facing downward and backward like shown on the picture on the right. For RHCP the longer cable of the phasing line has to be connected to the horizontal N-jack. If connectors are confused the antenna has LHCP instead of RHCP, and thus a loss of more than 10dB if the opposite station uses RHCP! take care....

Hint:

The black caps on the end of the connector box are only needed in the moment the box is filled with seal. Should they come out after years on the roof, the antenna's performance is not affected at all.



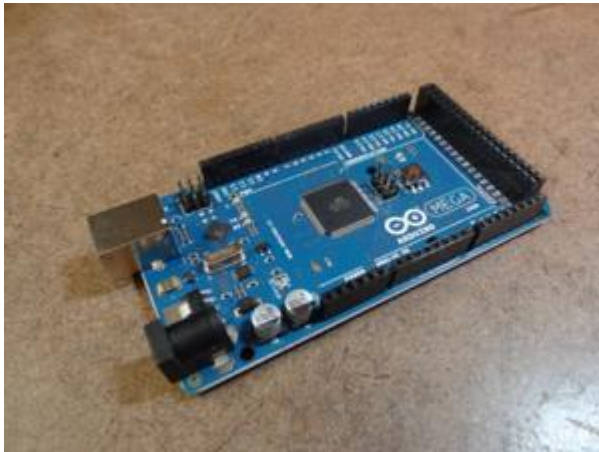
horizontal connector

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APPENDIX 3 ARDUINO SIMPLESAT ROTOR CONTROLLER [110]

The Arduino series of boards is an excellent choice for a satellite rotor controller. This controller uses the Yaesu GS-232 command set to control a Yaesu G-5500 Az-El rotor. The controller was designed to be compatible with the SatPC32 tracking program and should work with any tracking program that supports the Yaesu GS-232 format. This controller has been tested with the Arduino UNO and the Arduino Mega2560. Below is a picture of the Arduino Mega2560 board. The board has a USB interface and is capable of being powered from the USB port or an external power supply.



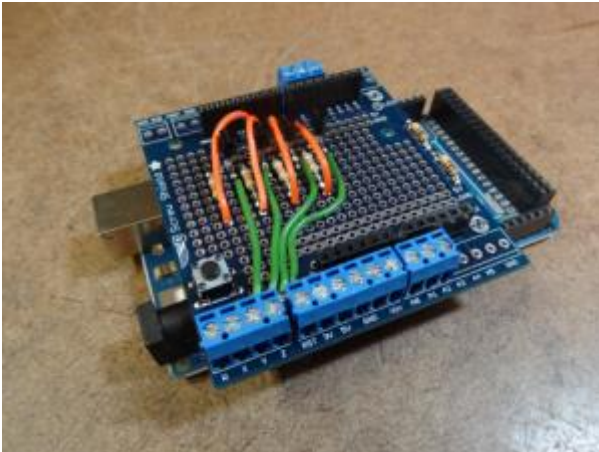
AdruinoRC-1

The Arduino series of boards are set up for plug in daughter boards (shields). There are a hundreds of different plug in shields available. I picked the ‘ #196 Proto Screw Shield’ from Adafruit Industries. The board offers screw terminals that are ideal for connecting to the cable that connects the controller to the G-5500 control box. The board also offers a prototype area which is used for the four 8.2K 1/4 watt resistors and four small signal npn transistors (2N4401 or equivalent) that are used to drive the UP, DOWN, LEFT and RIGHT control lines on the rotor control box. The picture below shows the completed daughter board.

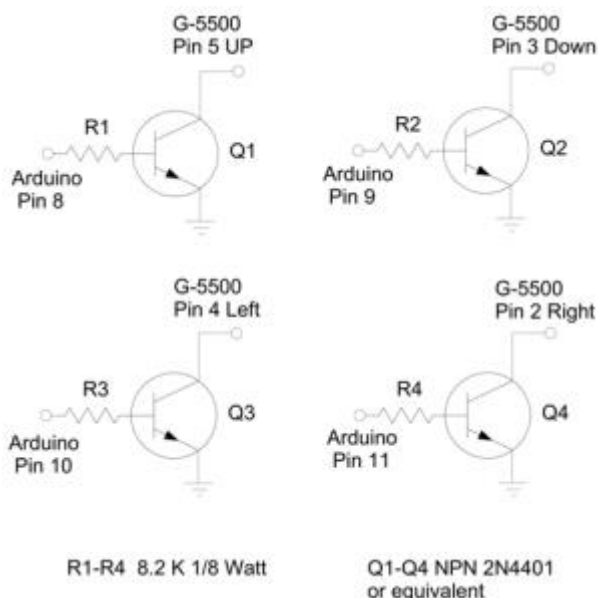


The next picture shows the completed daughter board plugged into the Arduino Mega2560 board. The four orange wires connect the four output pins (8, 9, 10 and 11)

that are used to control the rotor to the four 8.2K resistors. The other side of each resistor is connected to the base of an npn transistor. The collector of each transistor is connected (green wires) to one of the four output screw terminals (labelled W, X, Y and Z on the board). These four screw terminals connect to the UP, DOWN, LEFT and RIGHT pins on the G-5500 rotor control box. The emitter of each of the four transistors is connected to ground.

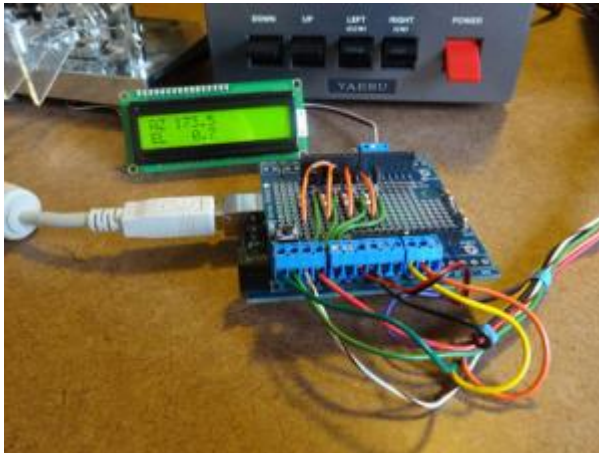


Here is the schematic for the parts on the shield board. The transistors are used as switches to isolate the G-5500 from the Arduino. There is no need to use relays with the G-5500. There are three additional connections to the G-5500. Pin 8 (Ground) on the G-5500 connects to ground on the shield board. Pin 6 (Azimuth analog voltage) on the G-5500 connects to pin A0 on the shield board. Pin 1 (Elevation analog voltage) connects to pin A1 on the shield board.



Below you will see the completed daughter board plugged into an Arduino UNO connected to the Yaesu rotor control box. The USB cable connects to the computer running SatPC32 and provides power to the controller. The controller can also be powered from an external power supply. Do NOT power the controller from the Yaesu rotor control box. The backlit serial LCD display is a 27977 from Parallax Inc. If you

plan on using the LCD display you might want to order a 805-00011 10-inch Extension Cable with 3-pin Header at the same time. The LCD display is not necessary for operation of the controller but is a very worthwhile addition.



APPENDIX 4 YAESU G5500 MANUAL AND SPECIFICATION LIST [88]

YAESU G-5500 ANTENNA AZIMUTH-ELEVATION ROTATORS & CONTROLLER



The Yaesu G-5500 provide 450° azimuth and 180° elevation control of medium- and large-size unidirectional satellite antenna arrays under remote control from the station operating position. The two factory-lubricated rotator units are housed in weatherproof melamine resin coated die-cast aluminum, to provide maintenance-free operation under all climatic conditions. The rotators may be mounted together on a mast, or independently with the azimuth rotator inside a tower and the elevation rotator on the mast.

The controller unit is a handsomely-styled desktop unit with dual meters and direction controls for azimuth, in compass direction and degrees; and elevation, from 0° to 180°. An External Control jack is provided on the rear of the controller for interfacing via D-to-A converters to an external microcomputer or other display/controller.

Please read this manual carefully before installing the rotators.

G-5500 Antenna Azimuth-Elevation Rotators & Controller Instruction Manual

SPECIFICATIONS

Voltage requirement:	110-120 or 200-240 VAC
Motor voltage:	24 VAC
Rotation time (approx., @60Hz):	Elevation (180°): 67 sec. Azimuth (360°): 58 sec.
Maximum continuous operation:	5 minutes
Rotation torque:	Elevation: 14 kg-m (101 ft-lbs) Azimuth: 6 kg-m (44 ft-lbs)
Braking torque:	Elevation: 40 kg-m (289 ft-lbs) Azimuth: 40 kg-m (289 ft-lbs)
Vertical load:	200 kg (440 lbs)
Pointing accuracy:	±4 percent
Wind surface area:	1 m ²
Control cables:	2 x 6 conductors - #20 AWG or larger
Mast diameter:	38-63 mm (1-1/2 to 2-1/2 inches)
Boom diameter:	32-43mm (1-1/4 to 1-5/8 inches)
Weight:	Rotators: 9 kg (20 lbs) Controller: 3 kg (6.6 lbs)

UNPACKING & INSPECTION

When unpacking the rotator confirm the presence of the following items:

Elevation Rotator Unit	1
Azimuth Rotator Unit	1
Controller Unit	1
Mast Clamp (pair)	2
Pipe clamp	2
U Bracket.....	1
M8 x 16 Hex. Bolt.....	4
M8 x 25 Hex. Bolt.....	8
M8 x 70 Hex. Bolt.....	4
M8 x 95 Hex. Socket Bolt	1
U-Bolt	2
6mm Spring Washer	4
6mm Flat Washer	4
8mm Spring Washer	18
8mm Flat Washer	12
M8 Square Nut	1
M8 Hex. Nut.....	4
M6 Hex. Nut.....	4
8-pin DIN Plug	1
7-pin Metal Connector	2
Water Resist Cap	2
Spare Fuse (117V:2A, 220V:1A).....	1
Instruction Manual	1

If any of these items are missing or appear to be damaged, save the carton and packing material and notify the shipping company (or dealer, if purchased directly at his shop).

Before proceeding with installation, confirm that the AC voltage label on the rear of the Controller matches your local line voltage: either "117V" for 110 to 120 VAC, or "220" for 220 to 240 VAC. If the labeled voltage range does not match, return the controller to the dealer from whom you purchased it (different power transformers are installed for the different voltage ranges).

Note that cable is not included with the rotator, as the length must be determined case-by-case. Contact your Yaesu dealer to obtain the length of cable your installation requires. For runs of over 100 feet, use #18 AWG instead of #20 AWG.

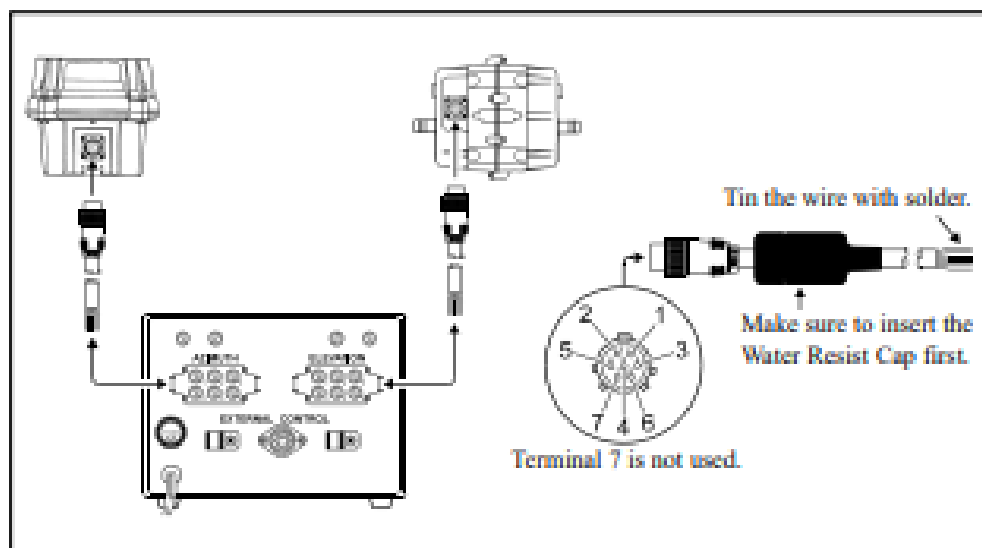
G-5500 Antenna Azimuth-Elevation Rotators & Contoroller Instruction Manual

CONTROL CABLE PREPARATION & CONNECTION

Before installing the antenna and rotators, make all connections and test rotator operation thoroughly on the ground as described below.

Your control cables should have six conductors each of at least #20 AWG gauge (if less than 100 feet long).

1. Assemble the cable according to the following diagrams.
2. Connect each wire to the terminals on the rear panel of the controller, making sure to match the numbers on the pins, and insert the connector to the Jack on the rotator.
3. On the controller, make sure that the **POWER** switch is in the "OFF" position, and connect the line cord to the AC power outlet.
4. Turn on the **POWER** switch. The meter lamps should light and the **ELEVATION** meter indicate to the center of the scale (90°).
5. Press the **UP** switch. The elevation rotator should turn as the meter indication moves to the right. Release the **UP** switch and confirm that the rotator slowly stops.
6. Repeat step 5, pressing the **DOWN** switch instead of the **UP** switch. The elevation rotator should turn in the opposite direction as the meter indication moves to the left.
7. If operation does not occur as described above, check for a wiring error in the elevation cable connections.
8. Press the **LEFT** switch. The azimuth rotator should turn counterclockwise as the meter indication moves to the left. Release the **LEFT** switch and confirm that the rotator slowly stops.
9. Repeat step 8, pressing the **RIGHT** switch instead of the **LEFT** switch. The azimuth rotator should turn clockwise as the meter indication moves to the right.
10. If operation does not occur as described in steps 8 and 9, check for a wiring error in the azimuth cable connections.
11. When everything checks out in the above steps, slide the water resist cap over the connectors on the rotator. Remove the cable clamps from the controller, clip them over the cables, and screw them back onto the controller. Then replace the two controller terminal covers.



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PRE-INSTALLATION ADJUSTMENT

Switch the controller off and adjust the **0. ADJ** screws beneath each meter face, if necessary, so that each meter points to the left edge of the scale. Then turn the controller back on for the following steps.

Azimuth Indicator

Press and hold the **LEFT** switch and allow the azimuth rotator to turn until it reaches its end stop. Note the precise position of the rotator (mark the housing, if necessary), and then press and hold the **RIGHT** switch to bring the rotator around one full turn to exactly the same position. The meter should now point precisely to 360° of the scale. If not, adjust the **FULL SCALE ADJ** potentiometer at the upper corner of the rear panel above the **AZIMUTH** terminals.

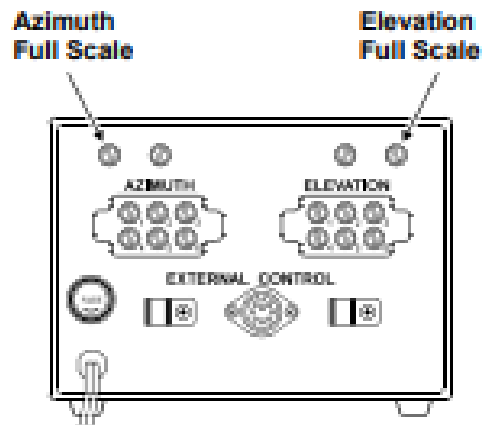
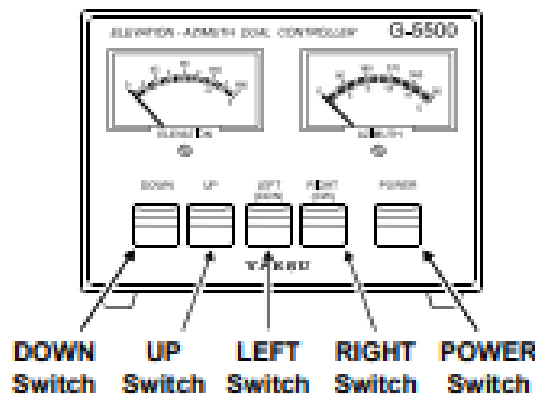
Press the **RIGHT** switch again to continue clockwise rotation until the rotator reaches its end-stop. The indicator should now point to right edge (90°) of the scale.

Elevation Indicator

Press the **UP** switch to align the 180° markers on the rotator. The meter should now point precisely to 180° at the right end of the scale. If not, adjust the **FULL SCALE ADJ** potentiometer at the upper corner of the rear panel above the **ELEVATION** terminals.

Notes on Controller Operation:

- The rotator motors are rated for five-minutes intermittent duty. However, they be brought to rest for at least 15 minutes afterwards.
- If both **UP** and **DOWN** switches or **RIGHT** and **LEFT** switches are pressed at the same time, the corresponding rotator turns up or right (clockwise).
- Release the switch when the meter indicates in the end zones (the rotator stops).
- Remember to turn the controller off when the rotators are not in use.

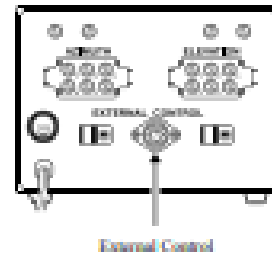
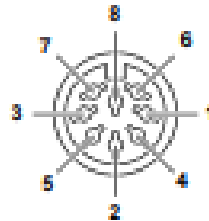


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EXTERNAL CONTROL

IF the optional GS-232 Computer Control Interfaces Unit is installed, the RS-232C cable from the computer routes through this grommet, and is affixed in place by the nylon cable clamp.

Pin	Function
6	Provides 2 to 4.5 VDC corresponding to 0 to 450 °
1	Provides 2 to 4.5 VDC corresponding to 0 to 180 °
4	Connect to Pin 8 to rotate left (counterclockwise)
2	Connect to Pin 8 to rotate right (clockwise)
5	Connect to Pin 8 to rotate down
3	Connect to Pin 8 to rotate up
7	Provides DC 13 V to 6 V at up to 200 mA
8	Common ground



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ROTATOR INSTALLATION

The maximum safe load of the G-5500 depends on the physical size of the antenna, method and quality of mechanical installation, and maximum wind velocity at the installation site.

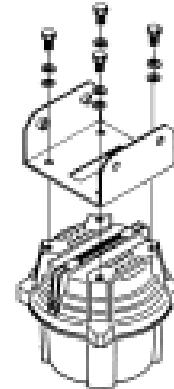
Notice that the preferred mounting method requires that each antenna be attached to the boom at its center of gravity, with the boom then attached to the elevation rotator at its center of gravity. This minimizes stress on the rotator and supporting structure, especially during strong winds.

The azimuth rotator may be mounted at the top of the mast together with the elevation rotator, or separately inside of a supporting tower. The latter method is generally stronger, and preferable in high wind locations or for large antennas, but requires some additional hardware not supplied with the G-5500 kits.

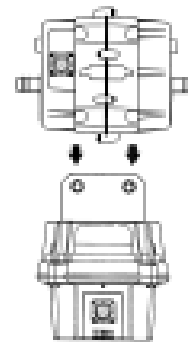
Mounting the Rotators Together

NOTE: If the elevation rotator is to be mounted on the mast alone, skip this section and see "Mounting the Rotators Separately".

1. Bolt the U-bracket to the top of the azimuth rotator using four M8x16 bolts, spring washers and flat washers.



2. Insert the elevation rotator into the U-bracket, then fasten the elevation rotator using four M8x25 bolts, spring washers and flat washers.

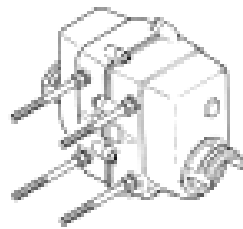


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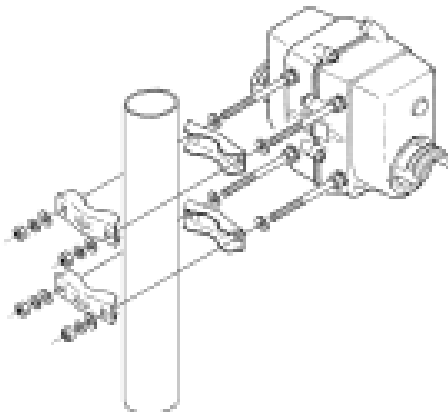
Mounting the Rotators Separately

Only do this if the elevation rotator is to be mounted alone on the mast. You will need four long stud bolts S8002738 and four additional pipe clamps S8003012 (available from your dealer).

1. Slip an 8 mm spring washer over the short-thread end of each stud bolt (x4), and screw the stud bolts firmly into holes in the side of the elevation rotator.



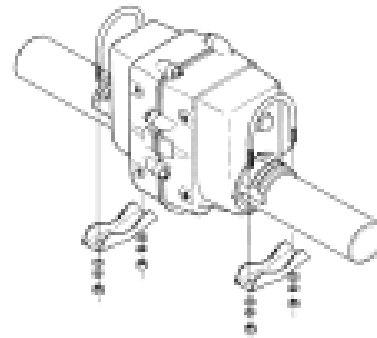
2. Slip an 8 mm flat washer over each installed stud bolt, and then the pipe clamps. Place another flat washer and then a spring washer over the end of each stud bolt, and start a nut on each to hold the hardware in place.



Installing the boom in the Elevation Rotator.

Do these steps for all installations.

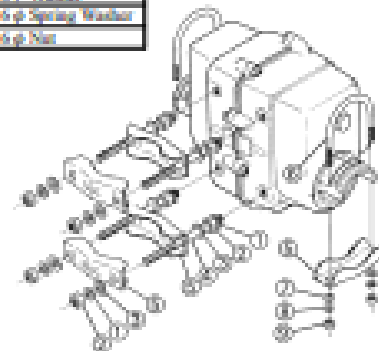
1. Slide the boom through the rotator.
2. Place one U-bolt over each arm of the rotator, and assemble one pipe clamp, flat washers, spring washers and nuts on the U-bolts. Center the boom carefully, and alternately tighten the nuts on each U-bolt 1/2-turn beyond the point where the spring washers are flattened.



Be sure to leave enough slack in both the elevation control cable and the coaxial cable feedline around the azimuth rotator so the antenna can rotate 450° without straining the cable or feedline.

For dual parallel arrays, feedlines should be taped to the boom on either side of the rotator, with enough slack left to allow 180° rotation without stressing the feedlines.

Qty.	Qty.	Description
1	8	8 # Spring Washer
2	8	8 # Nut
3	8	8 # Washer
4	4	8 # Stud Bolt
5	6	Boom Mast Clamp
6	2	U Bolt
7	4	6 # Washer
8	4	6 # Spring Washer
9	4	6 # Nut



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Mast Bracket Attachment in the Azimuth Rotator & Antenna Positioning

Important!! Before mounting the mast to the azimuth rotator, a single hole must be drilled through the bottom of the mast to accommodate an anti-twist support bolt used in the base support bracket halves:

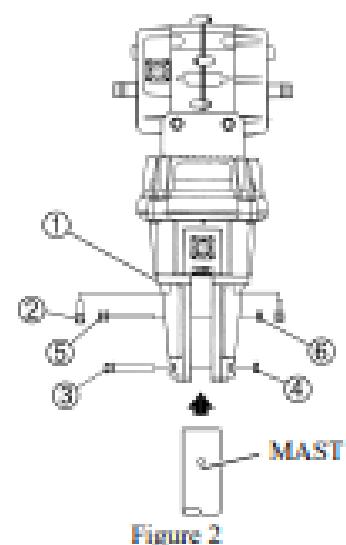
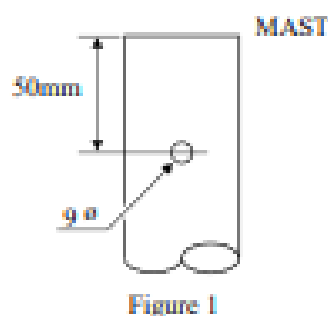
1. Drill a 9 mm diameter hole through both walls of the mast, centered 50 mm from the mast bottom (see Figure 1). Ensure the drill is maintained perpendicular and centered when making the hole, to ensure proper alignment of the holes in the mast and those in the base support clamp.
2. Referring to Figure 2, loosely fasten the mast bracket halves ① to the rotator housing using four M8x25 bolts ②, flat washers and spring washers.
3. Insert the mast into the bracket, and finger-tighten the four M8x70 bolts ③ with spring washers and nuts ④. Note that one side of the bracket has ridges on either side of the bolt holes: the bolts should be inserted from this side, so the ridges hold the bolt head from turning.
4. Finger-tighten the M8x95 socket bolt ⑤ with nut ⑥.
5. With the rotator connected, set the controller so that it indicates precisely 0° (North). Then, using an accurate map and known landmarks, position the antenna (without using the controller) so that it points to true North. Alternatively, consult a Geodetic Survey map for your area to determine the

Magnetic Deviation at your location, and then use a compass to position the antenna so that it points to true North (Magnetic North + Magnetic Deviation). Be careful not to disturb the antenna direction when tightening the mast bracket in the next step.












6. When you are satisfied with the orientation of the antenna, center the mast on the top of the azimuth rotator, and begin tightening the M8x25 bolts ② on each side alternately so that the gap on each side of the mast remains the same. Markings are provided on the top of the azimuth rotator to assist this process.
7. Confirm that the mast and bracket are precisely centered on the azimuth rotator, and tighten the four bolts ③ affixing the mast bracket to the top of the azimuth rotator.

Warning !!

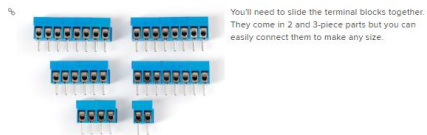
- Take care not overtighten the four bracket bolts. Do not torque the bolts beyond the point where the spring washer flattens.
- The azimuth rotator is designed for vertical mounting only. One half of the housing is marked "TOP SIDE". Water and contaminants will damage the motor unit if it is mounted horizontally or upside-down.



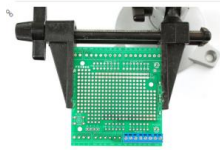
APPENDIX 5 #196 PROT SHIELD PART'S LIST. [111]

Image	Name	Description	Information & Distributor	Qty
		Printed circuit board	Adafruit	1
		2-position 3.5 terminal block	3.5mm terminals	6
		3-position 3.5 terminal block	3.5mm terminals	8
	LED1	3mm Red LED	Generic	1
	LED2	3mm Green LED	Generic	1
	R1 R2	470-1.0K Resistors for LED Carbon 5% 1/4W	Generic	2
	RESET S1	6mm tact switch	Generic	1
		8 pin female 0.1" stacky header (1x8)	Generic	2
		6 pin female 0.1" stacky header (1x6)	Generic	2
		10-pin stacking header	Generic	1
		2x3 pin stacking header	Generic	1

Appendices



You'll need to slide the terminal blocks together. They come in 2 and 3-piece parts but you can easily connect them to make any size.

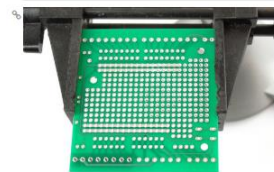


Get ready by putting the PCB in a vise. Then you can start by placing one of the 8-piece terminal blocks in the "Analog" breakout area.

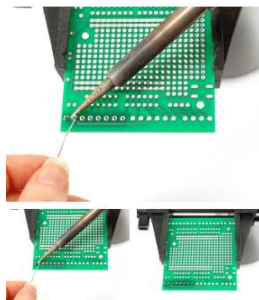


Check to make sure that the terminal blocks are facing the right way! You want the 'mouth' to face outward.

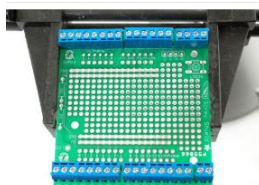
The terminal blocks should 'press fit' pretty nicely so they stay in place. If they seem a little loose, you can use tape to hold down the terminal blocks while you solder them.



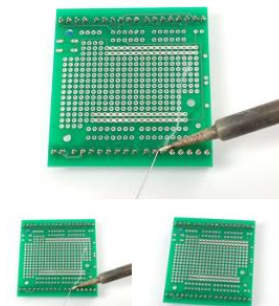
Flip over the PCB.



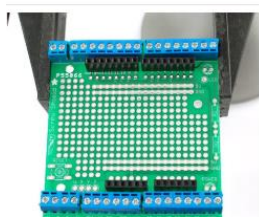
And solder the pins to the pads. Use plenty of solder so that you get the pads completely filled.



Place the remaining terminal blocks, checking again that they face the right direction!



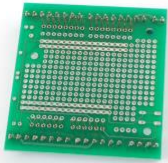
You can also just put the PCB with terminal blocks upside down on a table, which will keep the blocks in place while soldering.



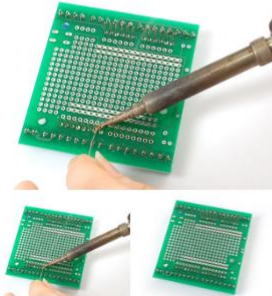
Next you can place the four 'stacking' headers. They go right next to the terminal blocks.

With the new R3 version, you'll use 1 pc 10pin stacking header, 2 pcs 8 stacking header and 1 pc 6 stacking header

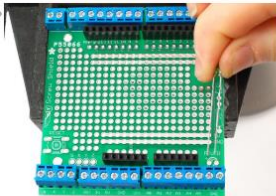
Low Cost and Portable Software Defined Radio Ground Station



Flip over the PCB, you can lay it down on a table again, just make sure that all the headers are sticking out straight.



Solder all the pins of the header with plenty of solder.

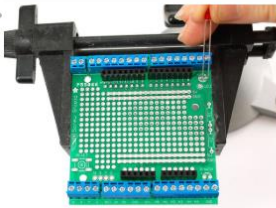


Next we'll place the two LEDs. The first LED is the green-colored one. This will tell us when the Arduino and shields are powered.

LED's are **directional** which means you need to place it in the right way or it wont work!

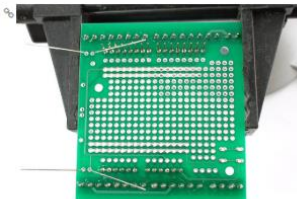
Check the LED to find the longer pin. This is the **positive** lead. That lead goes into the hole closest to the silkscreen '+'

In the image to the left, the longer lead is to the left.

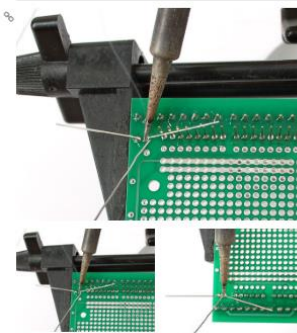


Next is the red LED. This LED can be used for pretty much whatever you want, although we suggest connecting it to pin 13 to act like a debugging LED.

Remember that the LED is directional, and the longer lead is positive. In the image to the left, the longer lead is to the left,

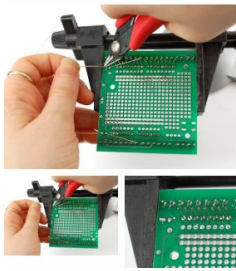


You can bent the LED leads out of the way to keep the LEDs flat against the PCB.



Solder both LEDs in place.

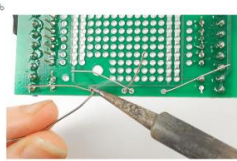
Appendices



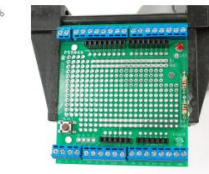
Use the diagonal cutters to clip the long LED legs. They should be cut just above the solder joint. This will keep them from shorting against stuff.



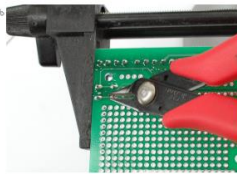
Next we will place the two 1.0Kohm resistors. These resistors are used to set the brightness of the LEDs. If you want brighter LEDs you can substitute 220 ohm resistors. If you want dimmer LEDs, you can use 4.7Kohm. Resistors do not have 'direction' so they can go either way and work fine. Place the two resistors into the silkscreen slots on the right of the PCB.



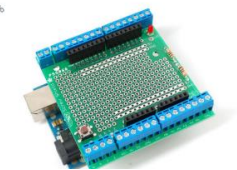
Solder and clip the two resistors.



Last we will place the reset switch. This switch will let you easily reset the Arduino. Tactile switches are symmetric, so you don't have to worry about putting them in wrong, and will snap into place flat against the PCB. Place the switch next to the **RESET** text.



Clip the tactile switch legs. They're pretty short but they are right on top of the DC jack so the shield will sit better if you clip them!



That's it! You can now insert the headers into the Arduino and start using the shield!

APPENDIX 6 SOFTWARE DOWNLOAD AND INSTALLATION INFORMATION

Software	Download site	Instructions
Sound Modem	http://uz7.ho.ua/packetradio.htm	Same as download site.
SDR#	https://airspy.com/download/	https://www.rtl-sdr.com/sdrsharp-users-guide/
SatPC32	http://www.dk1tb.de/downloadeng.htm	Same as download site.
VAC	https://www.vb-audio.com/Cable/	Same as download site.
AGW Online KISS	http://www.pe0sat.vgnet.nl/decoding/tlm-decoding-software/dk3wn/	Same as download site.
KissDUMP+	http://www.dk3wn.info/software.shtml	http://www.pe0sat.vgnet.nl/decoding/tlm-decoding-software/dk3wn/

APPENDIX 7 ROTATOR CODE [110]

```
/*
```

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INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR

PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE

LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT

OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER

DEALINGS IN THE SOFTWARE.

```
*/
```

```
// -----
```

```
// ----- you may wish to adjust these values -----
```

```
// -----
```

```
// A/D converter parameters
```

```
/*
```

AFTER you have adjusted your G-5500 control box as per the manual adjust the next 4 parameters. The settings interact a bit so you may have to go back and forth a few times. Remember the G-5500 rotors are not all that accurate (within 4 degrees at best) so try not to get too compulsive when making these adjustments.

```
*/
```

```
#if defined(ARDUINO) && ARDUINO >= 100
```

```
#include "Arduino.h"
```

```
#else
```

```
#include "WProgram.h"
```

```
#endif
```

```
#include <LiquidCrystal.h>
```

```
#include <SoftwareSerial.h> // use software uart library
```



```

const long _azAdZeroOffset = 325; // adjust to zero out lcd az reading when
control box az = 0

const long _elAdZeroOffset = 0; // adjust to zero out lcd el reading when control
box el = 0

/*
  10 bit A/D converters in the Arduino have a max value of 1023
  for the azimuth the A/D value of 1023 should correspond to 450 degrees
  for the elevation the A/D value of 1023 should correspond to 180 degrees
  integer math is used so the scale value is multiplied by 100 to maintain accuracy
  the scale factor should be 100 * (1023 / 450) for the azimuth
  the scale factor should be 100 * (1023 / 180) for the elevation
*/

// initialize the library by associating any needed LCD interface pin
// with the arduino pin number it is connected to
const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

const long _azScaleFactor = 232; // adjust as needed
const long _elScaleFactor = 568; // adjust as needed

// lcd display control
/*const byte _backLightOn = 0x11; // lcd back light on
const byte _cursorOff = 0x16; // lcd cursor off
const byte _clearScreen = 0x0C; // lcd clear screen
const byte _line0 = 0x80; // lcd line 0 - top line
const byte _line1 = 0x94;*/ // lcd line 1 - bottom line

// pins
const byte _azimuthInputPin = A0; // azimuth analog signal from G5500
const byte _elevationInputPin = A1; // elevation analog signal from G5500
const byte _G5500UpPin = 8; // elevation rotor up control line
const byte _G5500DownPin = 9; // elevation rotor down control line
const byte _G5500LeftPin = 10; // azimuth rotor left control line
const byte _G5500RightPin = 11; // azimuth rotor right control line

```

```

const byte _LcdTxPin = 7;      // software uart lcd tx pin
const byte _LcdRxPin = 6;      // software uart lcd rx pin - pin not used

// take care if you lower this value - wear or dirt on the pots in your rotors
// or A/D converter jitter may cause hunting if the value is too low.
long _closeEnough = 100; // tolerance for az-el match in rotor move in degrees * 100

// -----
// ----- values from here down should not need adjusting -----
// -----

// rotor
const long _maxRotorAzimuth = 45000L; // maximum rotor azimuth in degrees * 100
const long _maxRotorElevation = 18000L; // maximum rotor elevation in degrees *
100

long _rotorAzimuth = 0L; // current rotor azimuth in degrees * 100
long _rotorElevation = 0L; // current rotor azimuth in degrees * 100
long _azimuthTemp = 0L; // used for gs232 azimuth decoding
long _elevationTemp = 0L; // used for gs232 elevation decoding
long _newAzimuth = 0L; // new azimuth for rotor move
long _newElevation = 0L; // new elevation for rotor move
long _previousRotorAzimuth = 0L; // previous rotor azimuth in degrees * 100
long _previousRotorElevation = 0L; // previous rotor azimuth in degrees * 100

unsigned long _rtcLastDisplayUpdate = 0UL; // rtc at start of last loop
unsigned long _rtcLastRotorUpdate = 0UL; // rtc at start of last loop
unsigned long _displayUpdateInterval = 500UL; // display update interval in mS
unsigned long _rotorMoveUpdateInterval = 100UL; // rotor move check interval in mS

boolean _gs232WActice = false; // gs232 W command in process
int _gs232AzElIndex = 0; // position in gs232 Az El sequence
long _gs232Azimuth = 0; // gs232 Azimuth value
long _gs232Elevation = 0; // gs232 Elevation value
boolean _azimuthMove = false; // azimuth move needed
boolean _elevationMove = false; // elevation move needed

```

```

String azRotorMovement; // string for az rotor move display
String elRotorMovement; // string for el rotor move display

// create instance of NewSoftSerial
//SoftwareSerial lcdSerial = SoftwareSerial(_LcdRxPin, _LcdTxPin);

//
// run once at reset
//
void setup()
{

  lcd.begin(16, 2);
  // initialize rotor control pins as outputs
  pinMode(_G5500UpPin, OUTPUT);
  pinMode(_G5500DownPin, OUTPUT);
  pinMode(_G5500LeftPin, OUTPUT);
  pinMode(_G5500RightPin, OUTPUT);

  // set all the rotor control outputs low
  digitalWrite(_G5500UpPin, LOW);
  digitalWrite(_G5500DownPin, LOW);
  digitalWrite(_G5500LeftPin, LOW);
  digitalWrite(_G5500RightPin, LOW);

  // initialize serial ports:
  Serial.begin(9600); // control

  // initialize software uart used for lcd display
  pinMode(_LcdTxPin, OUTPUT);
  //lcdSerial.begin(9600);

  lcd.print("  W9KE V1.8  ");
  delay(2000);

```

```

lcd.clear(); //clears the whole screen


// set up rotor lcd display values
readAzimuth(); // get current azimuth from G-5500
_previousRotorAzimuth = _rotorAzimuth + 1000;
readElevation(); // get current elevation from G-5500
_previousRotorElevation = _rotorElevation + 1000;

}


//
// main program loop
//
void loop()
{
    // check for serial data
    if (Serial.available() > 0)
    {
        decodeGS232(Serial.read());
    }

    unsigned long rtcCurrent = millis(); // get current rtc value

    // check for rtc overflow - skip this cycle if overflow
    if (rtcCurrent > _rtcLastDisplayUpdate) // overflow if not true
        _rotorMoveUpdateInterval

    {
        // update rotor movement if necessary
        if (rtcCurrent - _rtcLastRotorUpdate > _rotorMoveUpdateInterval)
        {
            _rtcLastRotorUpdate = rtcCurrent; // reset rotor move timer base

            // AZIMUTH

```

```

readAzimuth(); // get current azimuth from G-5500 lcd.begin(16, 2);
// see if azimuth move is required
if ( (abs(_rotorAzimuth - _newAzimuth) > _closeEnough) && _azimuthMove )
{
    updateAzimuthMove();
}
else // no move required - turn off azimuth rotor
{
    digitalWrite(_G5500LeftPin, LOW);
    digitalWrite(_G5500RightPin, LOW);
    _azimuthMove = false;
    azRotorMovement = " "; //4 1

}

// ELEVATION
readElevation(); // get current elevation from G-5500
// see if aelevation move is required
if ( abs(_rotorElevation - _newElevation) > _closeEnough && _elevationMove )
// move required
{
    updateElevationMove();
}
else // no move required - turn off elevation rotor
{
    digitalWrite(_G5500UpPin, LOW);
    digitalWrite(_G5500DownPin, LOW);
    _elevationMove = false;
    elRotorMovement = " "; //5 2

}
} // end of update rotor move

// update display if necessary

```

```

if (rtcCurrent - _rtcLastDisplayUpdate > _displayUpdateInterval)
{
    // update rtcLast
    _rtcLastDisplayUpdate = rtcCurrent; // reset display update counter base
    displayAzEl(_rotorAzimuth, _rotorElevation);
}
}
else // rtc overflow - just in case
{
    // update rtcLast
    _rtcLastDisplayUpdate = rtcCurrent;
}
}

//
// update elevation rotor move
//
void updateElevationMove()
{
    // calculate rotor move
    long rotorMoveEl = _newElevation - _rotorElevation;

    if (rotorMoveEl > 0)
    {
        elRotorMovement = "_U_";
        elRotorMovement = elRotorMovement + String(_newElevation / 100);
        digitalWrite(_G5500DownPin, LOW);
        digitalWrite(_G5500UpPin, HIGH);
    }
    else
    {
        if (rotorMoveEl < 0)
        {
            elRotorMovement = "_D_";
            elRotorMovement = elRotorMovement + String(_newElevation / 100);
        }
    }
}

```

```

digitalWrite(_G5500UpPin, LOW);
digitalWrite(_G5500DownPin, HIGH);
}
}
}

//
// update azimuth rotor move
//
void updateAzimuthMove()
{
    // calculate rotor move
    long rotorMoveAz = _newAzimuth - _rotorAzimuth;
    // adjust move if necessary
    if (rotorMoveAz > 18000) // adjust move if > 180 degrees
    {
        rotorMoveAz = rotorMoveAz - 180;
    }
    else
    {
        if (rotorMoveAz < -18000) // adjust move if < -180 degrees
        {
            rotorMoveAz = rotorMoveAz + 18000;
        }
    }

    if (rotorMoveAz > 0)
    {
        azRotorMovement = "_R_";
        azRotorMovement = azRotorMovement + String(_newAzimuth / 100);
        digitalWrite(_G5500LeftPin, LOW);
        digitalWrite(_G5500RightPin, HIGH);
    }
    else
    {

```

```

    if (rotorMoveAz < 0)
    {
        azRotorMovement = "_L_";
        azRotorMovement = azRotorMovement + String(_newAzimuth / 100);
        digitalWrite(_G5500RightPin, LOW);
        digitalWrite(_G5500LeftPin, HIGH);
    }
}

//
// read azimuth from G5500
//
void readElevation()
{
    long sensorValue = analogRead(_elevationInputPin);
    _rotorElevation = ((sensorValue * 10000) / _elScaleFactor) - _elAdZeroOffset;
}

//
// read azimuth from G5500
//
void readAzimuth()
{
    long sensorValue = analogRead(_azimuthInputPin);
    _rotorAzimuth = ((sensorValue * 10000) / _azScaleFactor) - _azAdZeroOffset;
}

//
// decode gs232 commands
//
void decodeGS232(char character)
{

```



```

switch (character)
{
    case 'w': // gs232 W command
    case 'W':
    {
        {
            _gs232WActice = true;
            _gs232AzElIndex = 0;
        }
        break;
    }

    // numeric - azimuth and elevation digits
    case '0': case '1': case '2': case '3': case '4':
    case '5': case '6': case '7': case '8': case '9':
    {
        if ( _gs232WActice)
        {
            processAzElNumeric(character);
        }
    }

    default:
    {
        // ignore everything else
    }
}

//
// process az el numeric characters from gs232 W command
//
void processAzElNumeric(char character)
{
    switch(_gs232AzElIndex)

```

```

{
    case 0: // first azimuth character
    {
        _azimuthTemp =(character - 48) * 100;
        _gs232AzElIndex++;
        break;
    }

    case 1:
    {
        _azimuthTemp = _azimuthTemp + (character - 48) * 10;
        _gs232AzElIndex++;
        break;
    }

    case 2: // final azimuth character
    {
        _azimuthTemp = _azimuthTemp + (character - 48);
        _gs232AzElIndex++;

        // check for valid azimuth
        if ((_azimuthTemp * 100) > _maxRotorAzimuth)
        {
            _gs232WActice = false;
            _newAzimuth = 0L;
            _newElevation = 0L;
        }
        break;
    }

    case 3: // first elevation character
    {
        _elevationTemp =(character - 48) * 100;
        _gs232AzElIndex++;
        break;
    }
}

```

case 4:

```
{
    _elevationTemp = _elevationTemp + (character - 48) * 10;
    _gs232AzElIndex++;
    break;
}
```

case 5: // last elevation character

```
{
    _elevationTemp = _elevationTemp + (character - 48);
    _gs232AzElIndex++;

    // check for valid elevation
    if ((_elevationTemp * 100) > _maxRotorElevation)
    {
        _gs232WActice = false;
        _newAzimuth = 0L;
        _newElevation = 0L;
    }
    else // both azimuth and elevation are ok
    {
        // set up for rotor move
        _newAzimuth = _azimuthTemp * 100;
        _newElevation = _elevationTemp * 100;
        _azimuthMove = true;
        _elevationMove = true;
    }
    break;
}
```

default:

```
{
    // should never get here
}
}
```

```

}

//
// display az el on display
//
void displayAzEl(long az, long el)
{
    // display azimuth - filter A/D noise
    if (abs(_rotorAzimuth - _previousRotorAzimuth) > 50)
    {
        _previousRotorAzimuth = _rotorAzimuth;
        displayAz(az);
    }

    // display elevation - filter A/D noise
    if (abs(_rotorElevation - _previousRotorElevation) > 50)
    {
        _previousRotorElevation = _rotorElevation;
        displayEl(el);
    }
}

//
// display elevation - pad to length 8
// error message if < 0 or > max
//
void displayEl(long el)
{
    //clear elevation line lcdSerial
    //lcd.clear();

    lcd.print("          "); //Printing this and placing it before the setCursor clears away
    the block on the Elevation line

```

```
//lcd.setCursor(0,0);

// adjust value for display
double elFloat = el;
elFloat = elFloat / 100.0;

// position lcd cursor on bottom line
lcd.setCursor(0,0);

// display elevation
lcd.print("EL"); //println here introduces an ASCII character
// pad with spaces
if (elFloat < 10.0)
{
    lcd.print("");
}
if (elFloat < 100.0)
{
    lcd.print("");
}
lcd.print(elFloat, 1);
//lcd.print(elRotorMovement);
}

//
// display azimuth - pad to length 8
// error message if < 0 or > max
//
void displayAz(long az)
{
    // clear azimuth line
    //lcd.clear();
```

```

    lcd.print("          "); //Printing this and placing it before the setCursor clears away
the block on the Elevation line
    //lcd.setCursor(0,1); //Check this

```

```

// adjust value for display
double azFloat = az;
azFloat = azFloat / 100.0;

```

```

// position lcd cursor on top line
lcd.setCursor(0,1); //CR

```

```

// display azimuth
lcd.print("AZ");
    // pad with spaces
if (azFloat < 10.0)
{
    lcd.print("");
}
if (azFloat < 100.0)
{
    lcd.print("");
}
lcd.print(azFloat, 1);
//lcd.print(azRotorMovement);
}

```